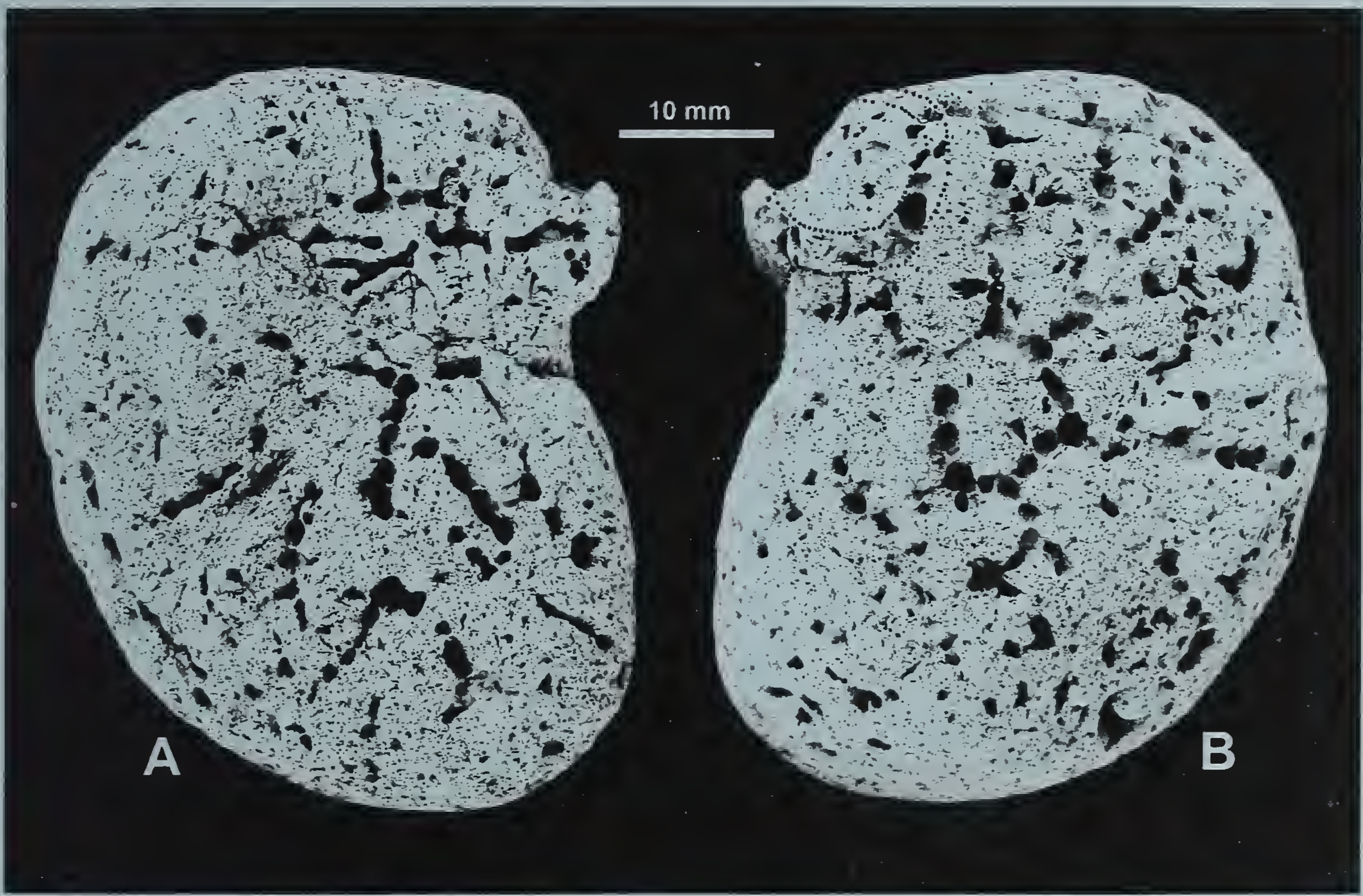
BULLETIN OF THE GEOLOGICAL SOCIETY OF NORFOLK

(FOR ARTICLES ON THE GEOLOGY OF EAST ANGLIA)

NO. 59 2009



Published 2010

CONTENTS INCLUDE

Hydrogeology of the North Norfolk coastal zone

Ancient and modern Sponge borings

BULLETIN OF THE GEOLOGICAL SOCIETY OF NORFOLK

No. 59 (2009) Published 2010

Editor: Julian E. Andrews

School of Environmental Sciences,
University of East Anglia,
Norwich NR4 7TJ

Telephone 01603 592536
FAX 01603 591327
E-mail J.Andrews@uea.ac.uk

EDITORIAL

This Bulletin contains two papers: the one by Green *et al.* is a detailed analysis of the hydrogeology of the coastal zone in north Norfolk. Catchment area, catchment typology and coastal geology are shown to be intimately linked to hydrogeological activity. The resulting conceptual hydrogeological model identifies several ground water discharge mechanisms. The UEA hydrogeological research group, led by Dr Kevin Hiscock, hope this work will form the geological basis for further publications on the contribution of groundwater flow to the coastal zone and attendant nutrient element budgets. The contribution of groundwater to the coastal ocean is surprisingly poorly constrained on both local and global scales.

The shorter paper by Donovan and Lewis describes sponge borings from a Chalk pebble collected on a Norfolk beach. Although one phase of boring on a belemnite guard occurred during Cretaceous times, a second phase is clearly modern: at least 70 million years passed between each phase of boring. With this pebble we quite literally hold time in our hands.

INSTRUCTIONS TO AUTHORS

Contributors should submit manuscripts as word-processor hard copy. We accept typewritten copy and will consider legible handwritten material for short articles only. When papers are accepted for publication we will request an electronic version. We can handle most word-processing formats although MS Word is preferred.

It is important that the style of the paper, in terms of overall format, capitalisation, punctuation etc. conforms as strictly as possible to that used in Vol. 53 of the Bulletin. Titles and first order headings should be capitalised, centred and in bold print. Second order headings should be centred, bold and lower case. Text should be 1½ line spaced. All measurements should be given in metric units.

References should be arranged alphabetically in the following style.

BALSON, P.S. & CAMERON, T.T.J. 1985. Quaternary mapping offshore East Anglia. *Modern Geology*, **9**, 221-239.

STEERS, J.A. 1960. Physiography and evolution: the physiography and evolution of Scolt Head Island. In: Steers, J.D. (ed.) *Scolt Head Island* (2nd ed.), 12-66, Heffer, Cambridge.

BLACK, R.M. 1988. *The Elements of Palaeontology*. 2nd Ed., Cambridge University Press, Cambridge. 404pp.

We prefer illustrations drawn with a computer graphics package. Thick lines, close stipple or patches of solid black or grey should be used with care as they can spread in printing. The editor may have diagrams re-drawn professionally and usually the GSN will cover the cost of this. Original illustrations should, before reproduction, be not more than **175mm by 255mm**. Full use should be made of the first (horizontal) dimension which corresponds to the width of print on the page, but the second (vertical) dimension is an upper limit only. Half tone photographic plates are acceptable provided the originals exhibit good contrast.

The editors welcome original research papers, notes, comments, discussion, and review articles relevant to the geology of **East Anglia** as a whole, and do not restrict consideration to articles covering Norfolk alone. All papers are independently refereed by at least one reviewer.

NOTES ON A CHALK PEBBLE FROM OVERSTRAND: ANCIENT AND MODERN SPONGE BORINGS MEET ON A NORFOLK BEACH

Stephen K. Donovan* & David N. Lewis[1]

Department of Geology, Nationaal Natuurhistorisch Museum - Naturalis,
Postbus 9517, NL-2300 RA Leiden, The Netherlands
[1]Department of Palaeontology, The Natural History Museum,
Cromwell Road, London, SW7 5BD, UK
*email: donovan@naturalis.nnm.nl

ABSTRACT

Two episodes of boring by clionid sponges in a chalk pebble from the beach at Overstrand, north Norfolk, are separated by at least 70 million years. A belemnite guard in the pebble includes Entobia*? isp. boreholes infilled with lithified chalk. This infestation of borers occurred between death and final burial, that is, during the Late Cretaceous. Other sponge borings, referred to* Entobia *isp. cf.* E. laquea *Bromley & d'Alessandro, 1984, cover the pebble's surface, lack a lithified infill and are obviously modern; some penetrate the belemnite guard. The age relationships of the borings were determined with relative ease in this beach pebble. However, if such a pebble had been preserved in a lithified conglomerate, it would be less accessible to examination and could present problems of interpretation.*

INTRODUCTION

Reworking of grains and clasts, including fossils, is a natural process by which many siliciclastic and some carbonate rocks are formed. Determination of the provenance of fossiliferous clasts in conglomerates is an important area of study in stratigraphy, sedimentology and taphonomy (e.g., Salvador, 1994, pp. 54-55; Martin, 1999, pp. 198-199; Rogers *et al.*, 2007). Two principal modes of reworking of fossils might be recognised. Particularly robust fossils might be reworked whole or as large fragments, such as the

Bull. geol. Soc. Norfolk (for 2009) **59**, 3-9 (Published 2010).

Maastrichtian (Upper Cretaceous) rudist bivalve *Titanosarcolites* Trechmann, which occurs as clasts in the siliciclastic flysch succession of the Paleogene Richmond Formation of eastern Jamaica (Pickerill *et al.*, 1995, p. 194). The chance of such reworking may be enhanced by early diagenetic mineralisation of shells. Secondly, lithoclasts may be reworked that contain identifiable fossils, such as the marine, fossiliferous Miocene limestones that commonly form clasts in the Pleistocene Farquahar's Beach red beds (Donovan & Miller, 1999, p. 35), another Jamaican example.

The specimen discussed in this paper falls into the second group, albeit in a setting much closer to home than Jamaica. The pebbles and cobbles that we find on our beaches might be regarded as conglomerates 'under construction,' clasts having formed by erosion of a host rock, and in the process of transport to a site where they might form part of a new lithified deposit. As such, they provide simple access to reworked rock fragments that would not be so easy to examine and interpret if re-lithified. Certainly, the present example has been easier to investigate 'in the round' than it would be if cemented into a cliff or quarry face.

We describe here a pebble found on a Norfolk beach. This pebble was one of many thousands that could have been collected, but, among all the specimens examined as part of this study, it provided a unique juxtaposition of an ancient trace fossil and a Recent boring of similar morphology. Descriptive terminology of borings follows Häntzschel (1975) and Bromley & d'Alessandro (1984, pp. 235-237, fig. 2). Our philosophy of open nomenclature follows Bengtson (1988).

MATERIAL AND METHODS

The chalk pebble described herein is deposited in the collections of the Nationaal Natuurhistorisch Museum - Naturalis, Leiden, NNM RGM 544 413. It was collected by the senior author on the beach at Overstrand, north Norfolk, approximate NGR TH 249 410, during July 2008. The beach at Overstrand, although dominantly sandy, also has numerous pebbles and cobbles of flint and, more rarely, chalk. Examination of this specimen was by hand lens and binocular microscope. For photography, it was coated with ammonium chloride (Feldmann, 1989) after being painted with black food colouring. Coloration was

Fig. 1. Two surfaces of a bored chalk pebble from the beach at Overstrand, north Norfolk, NNM RGM 544 413. (A) Slightly concave surface, belemnite top right. (B) Convex surface, belemnite top left. Outline of the belemnite is picked out by pecked line on B.

---

later removed by gentle washing with a dilute solution of household bleach and then water.

DESCRIPTION

The specimen is a bean-shaped, moderately well rounded pebble of chalk; it is flattest perpendicular to the plane of the paper in Figure 1. Its principal dimensions are 50.4 x 39.6 x 23.8 mm. One figured surface is gently concave (Fig. 1A) the other being moderately domed (Fig. 1B). Both of these surfaces have been quite densely bored, mainly by clionid sponges; borings are relatively rarer around the circumference between these surfaces. Borings are invariably preserved as open galleries or the surface expression of holes sub-vertical to vertical to the surface; most can be classed as growth phase B *sensu* Bromley & d'Alessandro (1984, fig. 2) and are referred to *Entobia* isp. cf. *E. laquea* Bromley & d'Alessandro (1984). None of these structures are infilled by mineral.

One macrofossil is apparent in the pebble, part of the guard of an indeterminate belemnite showing the typical brown coloration of specimens from the Cretaceous chalk (see outline in Fig. 1). This is positioned sub-perpendicular to the short axis of the pebble, and is itself, about 18.9 mm in length and 13.1 mm in diameter. The belemnite guard has also been bored by clionid sponges. Some of the borings are similarly preserved to those in the pebble and are not infilled; at least one is Recent, cross cutting both the chalk surface and the belemnite guard. Other borings in the belemnite guard are filled with lithified chalk (best seen in Fig. 1B), but these infestations are poorly seen and are referred only to *Entobia*? isp.

DISCUSSION

"You may not unnaturally suppose that the attempt to solve such problems as these can lead to no result, save that of entangling the inquirer in vague speculations, incapable of refutation and of verification. If such were really the case, I should have selected some other subject than a "piece of chalk" for my discourse" (Huxley, 1911, p. 2).

It is most probable that this chalk pebble and other clasts on the beach at Overstrand are local in origin. It is well known that the Chalk of north Norfolk extends from the Cenomanian to the Lower Maastrichtian; the latter is unusually young for the English Cretaceous succession (Chatwin, 1961, p. 35; Peake & Hancock, 1961; Rawson *et al.*, 1978, pp. 30, 52; Moorlock *et al.*, 2002, pp. 3-5). The only macropalaeontological data in RGM 544 413 is provided by the (indeterminate) belemnite guard, a group in which the Norfolk Cretaceous strata are particularly rich at several levels (e.g., Peake & Hancock, 1961; Godwin, 1998a, b; Whittlesea, 2005, 2006, 2007; and references therein). The specimen is at least of Late Cretaceous age (*circa* 70 million years) and the older it is, the greater the time interval separating the two episodes of boring.

The principal fascination with the surface of this pebble is that it imperfectly separates, by what might be regarded as an 'unconformity on a micro scale', clionid sponge borings (*Entobia*) that were formed in both Cretaceous and post-Cretaceous times. The post-Cretaceous borings are almost certainly Recent, unless the pebble was earlier reworked into a late Cenozoic deposit and has now been liberated, once again, by erosion. In the absence for any evidence to the contrary, such as any distinctive staining of the chalk, it is conservative to regard the younger borings as being the result of Recent activity.

Exposure of Recent clionid sponge borings in the chalk demonstrates that the surface of the pebble has been eroded since it was bored. The structures exposed were mainly internal within the hard substrate during the life of the sponges (Bromley & d'Alessandro, 1984), but these borings doubtless weakened the strength of the chalk matrix close to the surface. The occurrence of borings on both sides of the pebble indicates that it was probably rolled around on the sea floor, exposing alternate surfaces to infestation. The rarity of borings around the periphery suggests that either this surface was invariably partially buried by sediment after rolling and thus not infested or, perhaps more likely, this region was more easily eroded than the two faces and has thus lost any evidence of infestation. This surface erosion has removed the chalk down to the level of the chambers. Some of these borings also penetrate the belemnite guard, but others are undoubtedly ancient as demonstrated by their infill of lithified chalk. The initial boring of the belemnite undoubtedly occurred between its death and final burial.

Unusually, this specimen preserves similar borings that were made in hard substrates over 70 million years apart; one substrate, the belemnite guard, was infested by both Cretaceous and Recent borers. In the Late Cretaceous, following decomposition and/or predation or scavenging of the belemnite animal, the guard formed a hard substrate for sponge infestation; in the Recent, the belemnite guard, again, and the now lithified chalk were both infested. The lithified chalk extends into some of the borings in the belemnite, but never into the Recent borings in the chalk, providing evidence for the ancient origin of the former. The relative timing of the two episodes of sponge boring in this specimen was determined with relative ease as a beach pebble, but, if found as a clast cemented in a lithified conglomerate, the key surfaces might be obscured and the difference in the ages of borings would be more difficult to determine.

ACKNOWLEDGEMENTS

S.K.D. thanks his children, Hannah and Pelham, for their patience with his obsessive rock collecting whenever we visited the beach at Overstrand on what was, after all, a holiday! We thank Phil Crabb (Photographic Unit, The Natural History Museum) for the images. The constructive comments of two anonymous reviewers are gratefully acknowledged.

REFERENCES

BENGTSON, P. 1988. Open nomenclature. *Palaeontology*, **31**, 223-227.

BROMLEY, R.G. & ALESSANDRO, A. D' 1984. The ichnogenus *Entobia* from the Miocene, Pliocene and Pleistocene of southern Italy. *Rivista Italiana di Paleontologia e Stratigrafia*, **90**, 227-296.

CHATWIN, C.P. 1961. *British Regional Geology. East Anglia and Adjoining Areas* (4th edition). Her Majesty's Stationery Office, London, vi+100 pp.

DONOVAN, S.K. & MILLER, D.J. 1999. Report of a field meeting to south-central Jamaica, 23rd May, 1998. *Journal of the Geological Society of Jamaica*, **33** (for 1998), 31-41.

FELDMANN, R.M. 1989. Whitening fossils for photographic purposes. In: Feldmann, R.M., Chapman, R.E. & Hannibal, J.T. (eds) *Paleotechniques*. Paleontological Society Special Publication, **4**, 342-346.

GODWIN, M. 1998a. Growth rings and populations dynamics of *Belemnitella* in the Beeston Chalk, Upper Campanian, Caistor St. Edmund, Norfolk. *Bulletin of the Geological Society of Norfolk*, **47**, 3-18.

GODWIN, M. 1998b. A note on the possible occurrence of *Belemnitella* cf. *americana*? (Morton) in the Beeston Chalk, Upper Campanian, Norfolk. *Bulletin of the Geological Society of Norfolk*, **47**, 19-22.

HÄNTZSCHEL, W. 1975. Trace fossils and problematica (2nd edition, revised and enlarged). In: Teichert, C. (ed.) *Treatise on Invertebrate Paleontology, Part W, Miscellanea, Supplement 1*. Geological Society of America and University of Kansas Press, Boulder and Lawrence, xxi + 269 pp.

HUXLEY, T.H. 1911. On a piece of chalk [1868]. In: Huxley, T.H. *Lectures and Lay Sermons*, 1-21. Dent and Sons, London, xvii+294 pp.

MARTIN, R.E. 1999. *Taphonomy: A Process Approach*. Cambridge University Press, Cambridge, xvi+508 pp.

MOORLOCK, B.S.P., HAMBLIN, R.J.O., BOOTH, S.J., KESSLER, H., WOODS, M.A. & HOBBS, P.R.N. 2002. *Geology of the Cromer district – a brief explanation of the geological map Sheet 131 Cromer*. British Geological Survey, Keyworth, ii+34 pp.

PEAKE, N.B. & HANCOCK, J.M. 1961. The Upper Cretaceous of Norfolk. In: Larwood, G.P. & Funnell, B.M. (eds) *The Geology of Norfolk*, 293-339. Transactions of the Norfolk and Norwich Naturalists' Society, **19**, 269-375.

PICKERILL, R.K., DONOVAN, S.K. & DUNN, J.T. 1995. Enigmatic cobbles and boulders in the Paleogene Richmond Formation of eastern Jamaica. *Caribbean Journal of Science*, **31**, 185-199.

RAWSON, P.F., CURRY, D., DILLEY, F.C., HANCOCK, J.M., KENNEDY, W.J., NEALE, J.W., WOOD, C.J. & WORSSAM, B.C. 1978. A correlation of the Cretaceous rocks of the British Isles. *Geological Society, London, Special Report*, **9**, 1-70.

ROGERS, R.R., EBERTH, D.A. & FIORILLO, A.R. 2007. *Bonebeds: Genesis, Analysis, and Paleobiological Significance*. University of Chicago Press, Chicago, 400 pp.

SALVADOR, A. (ed.). 1994. *International Stratigraphic Guide: A Guide to Stratigraphic Classification, Terminology, and Procedure* (2nd edition). International Union of Geological Sciences and Geological Society of America, Trondheim and Boulder, xix+214 pp.

WHITTLESEA, P. 2005. First record of phragmocone and alveolar cavity of the chalk belemnite *Gonioteuthis*. *Bulletin of the Geological Society of Norfolk*, **54**, 15-23.

WHITTLESEA, P. 2006. The intertidal outcrop of the Upper Campanian Beeston Chalk between Sheringham and West Runton, Norfolk. *Bulletin of the Geological Society of Norfolk*, **56**, 3-32.

WHITTLESEA, P. 2007. Correlating the inland and coastal Beeston Chalk of Norfolk. *Bulletin of the Geological Society of Norfolk*, **57**, 9-32.

[Manuscript received 23 October 2008; revision accepted 8 December 2008]

THE HYDROGEOLOGY OF THE COASTAL ZONE OF NORTH NORFOLK

Adrian R. Green, Kevin M. Hiscock and Julian E. Andrews*

School of Environmental Sciences,
University of East Anglia, Norwich, NR4 7TJ, U.K.
*Present address: RPS Planning and Development, Conrad House, Beaufort Square,
Chepstow, Monmouthshire, NP16 5QG, U.K.

ABSTRACT

This paper describes the nature and relative significance of groundwater discharge to the coastal zone of North Norfolk, assessed from the integration of geological information and results from field surveys of groundwater occurrence and salinity. The complex hydrogeology of the barrier coastline is found to be dependent on the inland groundwater catchment area and the geology and tidal regime of the coastal zone. Along the western half of the barrier coastline, west from the River Burn, there is a zone of active groundwater influx determined by a large Chalk groundwater catchment area and a coastal geology dominated by thin Holocene marsh deposits with a high component of permeable coarse clastics (sands and gravels). In contrast, in the eastern half of the coastline, the salt marsh between Wells-next-the-Sea and the mouth of the River Stiffkey is a zone of low groundwater influx controlled by a small groundwater catchment area and with a geology characterised by thick Holocene back-barrier deposits with little coarse clastic material. The remaining coastal sections of reclaimed salt marsh are characterised by a low to moderate groundwater inflow and the presence of glacial sand and gravel beneath Holocene marsh deposits. A hydrogeological conceptual model is presented that identifies several groundwater flow mechanisms of potential groundwater discharge within the coastal system of North Norfolk that demonstrate various pathways for groundwater transfer including: (a) at the land-marsh boundary; (b) to the Holocene marsh deposits; (c) from the beach and dune barrier system; and (d) from the underlying Chalk directly to the sea.

Bull. geol. Soc. Norfolk (for 2009) **59**, 10–52 (with appendices p. 53-83) (Published 2010).

INTRODUCTION

The coastline of North Norfolk is renowned for its landscape value and as an area of international significance for its natural and reclaimed coastal habitats. At the national level, the area is designated an Area of Outstanding Natural Beauty and is protected at the European level by designation as a Special Area of Conservation and a Special Protection Area under the EC Habitats Directive (92/43/EEC) and Birds Directive (79/409/EEC). Understanding the mechanisms that determine the distribution of freshwater and saltwater within the coastal zone is therefore essential to its management and protection. In this context, the study presented here provides a description of the hydrogeology of the 'barrier coastline' of North Norfolk, and determines the nature and significance of groundwater discharge to the coastal environment.

The mechanisms of groundwater discharge active within a complex coastal system, such as that of North Norfolk, are principally controlled by the combined effect of coastal geology, geomorphology, physiography and the inland groundwater catchment characteristics. In this paper, lateral and seaward variations in the physical characteristics and vegetation observed within the coastal zone are first described. For the purpose of this study, the coastal zone is sub-divided into type-sections that share similar hydrogeological characteristics and these features are described. The results obtained from field surveys undertaken within the coastal zone are then presented, from which a generic conceptual model of coastal hydrogeology for North Norfolk is derived.

MODERN COASTAL GEOMORPHOLOGY AND PHYSIOGRAPHY

Geomorphological structure

The dominantly macro-tidal regime with mean spring tides of 4.7 m at Cromer to 6.6 m at Hunstanton (Admiralty Tide Tables) and the shallow offshore gradient have allowed the development of an extensive 'barrier' system with a wide littoral zone along this section of the East Anglian coastline. The basic features of the North Norfolk barrier system comprise three distinct zones: (1) back-barrier saltmarsh and inter-tidal mud flats; (2) sand and gravel barrier structures; and (3) inter-tidal sand flats seaward of the barriers.

Surface hydrology and tidal drainage network

At low tide, six 'estuary' channels drain the North Norfolk coastal zone (Fig. 1). Outflow from these channels during the ebb-tide is a complex mixture of water from several sources,

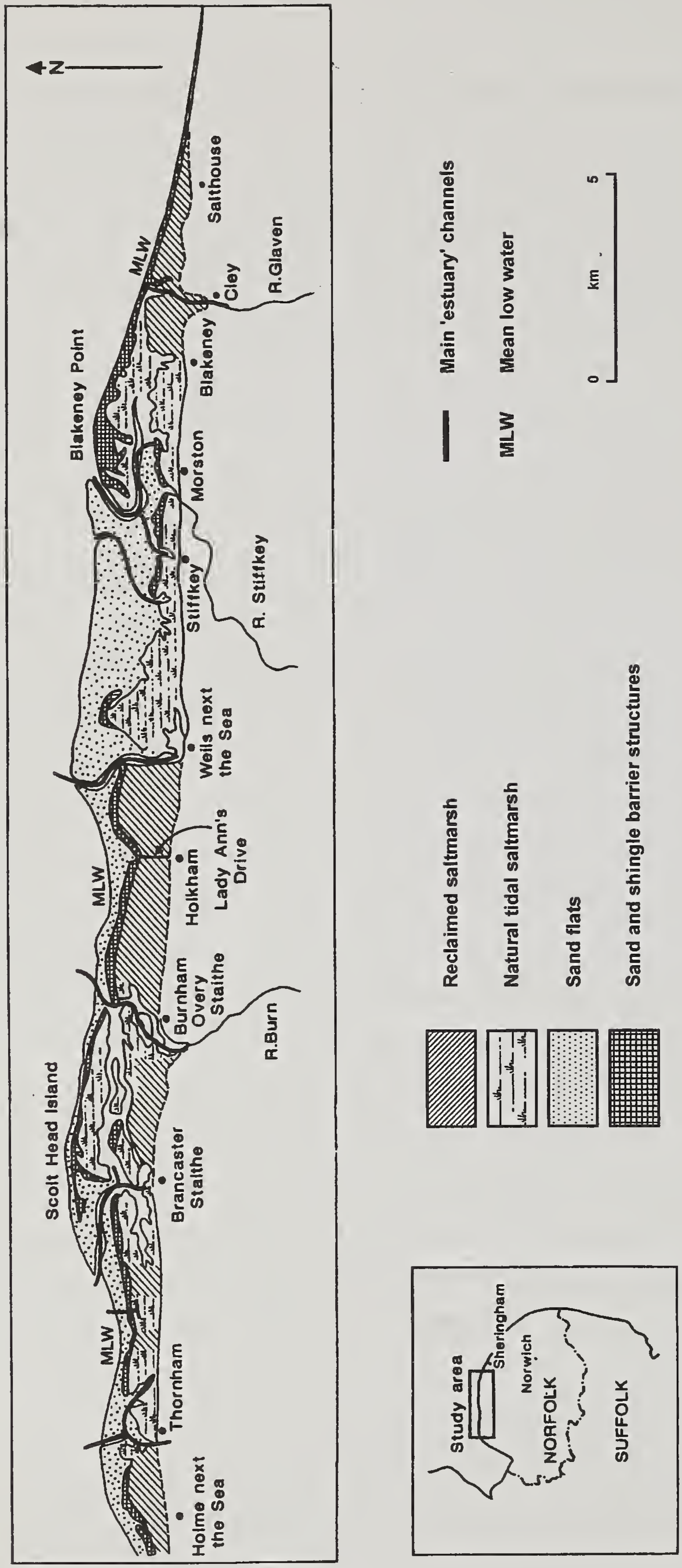


Fig. 1. Map of the North Norfolk coastal barrier complex showing the main sedimentary environments, adapted from Funnell (1992).

each with its own characteristic salinity and chemistry. These sources include: (1) draining seawater from the tidal prism that inundates the coastal system during each flood tide; (2) fresh surface water discharge from the rivers draining inland catchment areas; (3) fresh or brackish water discharged from reclaimed marsh systems; (4) runoff from urban areas at the land-marsh boundary; (5) discharge from non-tidal land drains that de-water agricultural land along the coastal boundary; (6) direct precipitation to the coastal creek system; and (7) the discharge of fresh or brackish groundwater and/or marsh porewater directly to the creeks.

All the tidal creeks that dissect the back-barrier saltmarshes and mudflats ultimately discharge into one of the estuary channels. Creeks tend to be incised features with a bottom elevation approximately 1 to 2 m below the adjacent marsh surface. Despite the large tidal range characteristic of the Norfolk coastal zone, the upper marsh usually remains emergent throughout the tidal cycle with submergence beneath tidal water restricted to high spring tides and storm surge tides. Tidal creeks that cross the lower marsh or un-vegetated mudflats are completely submerged on a more frequent basis.

The variation in water level observed over a tidal cycle is characterised by a rapid rise and fall in water levels over approximately 5 hours (the 'flood-ebb tidal surge') followed by a longer period of slow drainage (approximately 7 - 7½ hours) during which the water depth is shallow, relatively constant, and the creek system dewaters by gravity drainage (the period of 'ebb-tide drainage'). This particular tidal regime is common to all creeks within the North Norfolk saltmarsh system and implies that the majority of seawater that inundates the coastal marsh during each flood-ebb surge is effectively drained from the saltmarsh system during each complete tidal cycle.

Present coastal sedimentary environments

Pearson *et al.* (1990) identified eleven 'environmental units' within the coastal system of North Norfolk of which six were sedimentary zones. The low energy environment developed behind the coastal barrier structures of North Norfolk allows the accumulation of a considerable thickness of largely inorganic, fine-grained, muddy deposits. Much of the inter-tidal mud is colonised by vegetation communities that constitute classic 'saltmarsh' habitat. However, in low-lying sheltered areas or within the complex network of tidal creeks that drain the back-barrier saltmarshes, an un-vegetated inter-tidal mud unit dominates.

The sand and gravel barrier structures along this stretch of coastline occur either as actively accreting spits (e.g. Blakeney Point), narrow dune ridges (e.g. Morston to Wells) or large barrier islands such as Scolt Head (Andrews *et al.*, 2000). They are generally fronted

by a zone of inter-tidal sand flats which are often reworked by strong tidal and wave action into a variety of sedimentary structures, such as beach bars and mega-ripples (Pearson *et al.*, 1990). The width of the sand flat zone varies from 0.25 km to 1.75 km, although it is effectively absent in front of Blakeney Point spit in the extreme east of the area (Fig. 1).

The seaward zonation of the barrier system generally comprises back-barrier saltmarsh and inter-tidal mudflats, sand and gravel barrier structures and inter-tidal sand flats, and is observed along almost the entire length of the Norfolk barrier coast (Fig. 1). At low tide, the width of the entire barrier system is approximately 2.0 km to 2.5 km, although it does exceed 3.5 km in places (e.g. at Wells-next-the-Sea). The natural extent and arrangement of these basic features of the coastal zone have been altered by the reclamation of previously tidal saltmarsh, the construction of artificial sea defences and the modification and redirection of the tidal river estuaries. This dynamic stretch of coastline therefore comprises a complex arrangement of accreting, eroding and apparently stable sections. The presence of remnant exposures of saltmarsh deposits within the inter-tidal sand flats (seaward of barrier structures) suggests general coastal erosion and roll-back during the late Holocene, and implies an increasing pressure on coastal habitats along this section of coastline.

Vegetational zonation in the coastal zone

The generalised succession of vegetation communities within the saltmarshes of North Norfolk is summarised in Fig. 2. The complex zonation of coastal vegetation occurs largely in response to variations in salinity and porewater conditions across the surface of the marsh. These conditions are primarily controlled by the frequency and duration of tidal submergence, which is in turn dependent on the relationship between the local tidal regime and marsh elevation. Other factors, such as substrate type, can also control zonation where these affect locally important marsh characteristics such as drainage capacity or the ability of pioneer communities to first colonise new marsh surfaces.

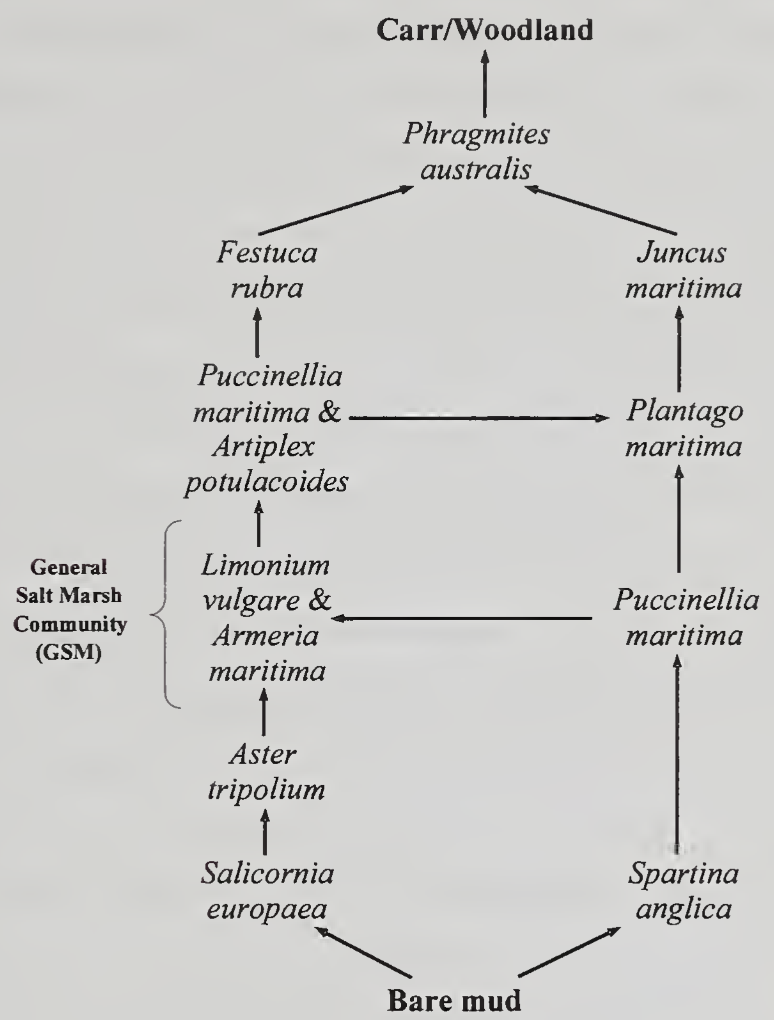


Fig. 2. Generalised succession of dominant vegetation on the saltmarshes of North Norfolk, following colonisation of bare tidal muds (after Packham & Willis, 1997).

Almost all of the communities identified in Fig. 2 are halophytes; plants able to grow and complete their life cycle in a saline environment, with salt concentrations greater than 100-200 mM NaCl (5800-11,600 mg l^{-1} NaCl) (Flowers *et al.*, 1986). The succession passes from pioneer and lower marsh communities that first develop on low-lying, frequently-submerged, saline mudflats, through mixed mid- and upper-marsh communities, to largely terrestrial communities at the land-marsh boundary. A characteristic feature of the saltmarsh system of North Norfolk is the preponderance of the co-dominant General Salt Marsh (GSM) community (Chapman, 1976). The GSM community typically includes varying proportions of Sea Lavender (*Limonium vulgare*), Sea Pink (*Armeria maritima*), Sea Plantain (*Plantago maritima*), Sea Arrowgrass (*Triglochin maritima*), *Spergula marginata* and Sea Purslane (*Halimione portulacoides).*

To simplify this complex succession, saltmarsh systems are often divided into 'high marsh' and 'low marsh' communities defined by the topographic elevation of the marsh surface and the local saltmarsh flora. Pearson *et al.* (1990) mapped the distribution of eight different 'vegetation units' in North Norfolk, although the majority of the coastal zone is dominated by an 'Upper Marsh Community' and a 'Lower Marsh Community' defined by the first appearance of Sea Purslane (*Halimione portulacoides*).

A key feature of the distribution maps of Pearson *et al.* (1990) is the presence of extensive tidal reed beds (*Phragmites*) along much of the tidal land-marsh boundary west of Holkham (NGR approximately TF 892 438). *Phragmites australis* (National Vegetation Classification community S5) is a salt tolerant reed recognised as one that marks the transition from a saline inter-tidal environment to a terrestrial freshwater environment inland (Wheeler *et al.* 2004). In the absence of any major surface water input to the western marshes, the persistence of *Phragmites* at a considerable distance from the land-marsh boundary (greater than 300 m at Thornham) implies the influence of a source of freshwater, presumably groundwater, within the coastal marsh system in these areas.

GEOLOGY AND STRUCTURE OF THE COASTAL ZONE

Overview

An understanding of the coastal geology of North Norfolk is required such that the influence of present surface sedimentary environments on the hydrogeology of the coastal zone can be assessed. For the purpose of this study, the coastal zone geology is restricted to the following divisions: (1) Cretaceous Chalk; (2) Pleistocene 'Pre-Glacial' and 'Glacial' deposits; and (3) Holocene 'Post-Glacial' deposits.

Cretaceous Chalk

Cretaceous Chalk underlies the entire coastal zone of North Norfolk. Rather than forming a simple wave-cut coastal platform, seismic refraction data revealed an easterly plunging trough in the Chalk surface beneath the coastal marshes of North Norfolk (Chroston *et al.*, 1999). Using this seismic data and all available geological data (this research; Environment Agency/British Geological Survey (BGS) archives; Funnell and Pearson, 1989; Boomer, 1997; AEG Ltd., Salthouse flood protection data, October 1998), a contour map of the eroded Chalk surface has been constructed (Figs 3a and 3b). As borehole log data for the coastal zone are sparse, the following assumptions have been made:

- In the absence of ground-truth borehole data, the elevation of the Chalk surface identified on seismic profiles is taken as an accurate estimate of true elevation.
- The trough occurs as a distinct valley structure along the entire length of the coastline with a steeper southern margin and shallower northern margin.
- The northern margin of the trough is defined by a subdued ridge of Chalk, beyond which the Chalk surface dips gently to the north (seaward) away from the ridge.
- Formation of the trough was coeval with formation of 'buried channel' structures that underlie the six principal watercourses that discharge to the sea along this section of coastline (see above and Fig. 1).

The morphology of the trough is largely constrained by evidence from the seismic profile data, but augmented with some auger and core information (Andrews *et al.*, 2000). Trough morphology is least well constrained in the western half of the study area, although there is circumstantial evidence for its presence (Funnell and Pearson, 1989) even as far west as Holme-next-the Sea (Fig. 1).

The trough in the Chalk surface is a sinuous feature running sub-parallel to the coastline and extending offshore in the extreme east of the study area (i.e. east of Salthouse, Fig. 3b). The axis of the trough is generally located beneath the centre of the coastal saltmarshes where it attains elevations as low as -20 m OD in places. In the western half of the study area, between Thornham and Holkham (Fig. 3a), the southern margin of the trough is located south (i.e. landward) of the land-marsh boundary. East of Holkham the trough is situated entirely beneath the coastal marshes with its southern margin coincident with the present land-marsh boundary.

Although the age of trough formation in the Chalk surface is not certain (see below), the strong east-west linearity of this feature suggests a degree of structural control on its formation, possibly linked to east-west marginal faulting of the London-Brabant Massif (Chroston *et al.*, 1999). The trough is infilled with a complex sequence of Holocene deposits (associated with barrier and back-barrier sedimentation), glacial till and glaciofluvial sand and gravel, as described below.

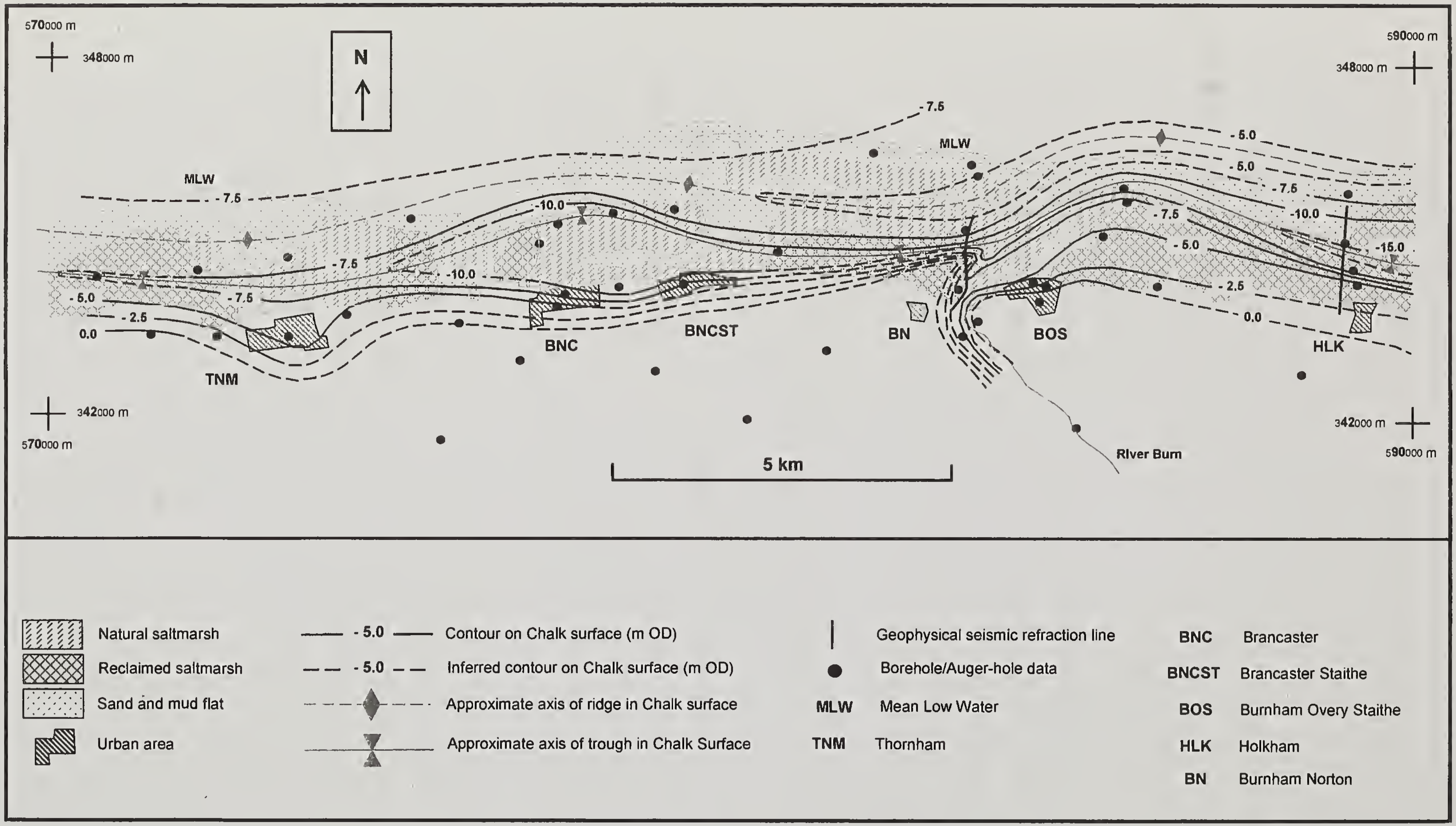


Fig. 3a. Contour map of the Chalk surface beneath the North Norfolk coastal margin, mapped relative to Ordnance Datum, based on borehole, auger and geophysical data. (a) Western coastal margin (Thornham to Holkham).

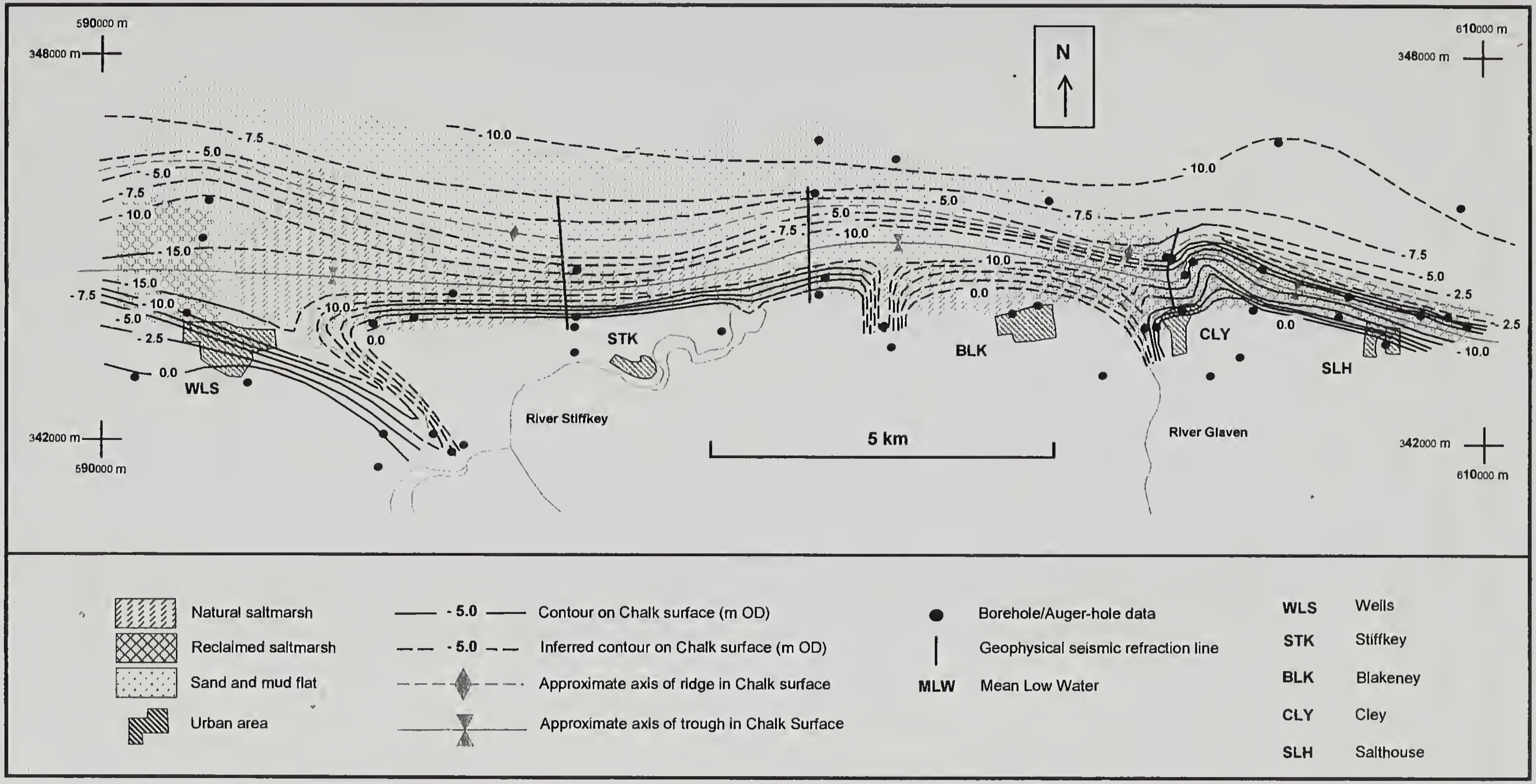


Fig. 3b. Contour map of the Chalk surface beneath the North Norfolk coastal margin, mapped relative to Ordnance Datum based on borehole, auger and geophysical data. (b) Eastern coastal margin (Wells to Salthouse).

Pleistocene geology

Contours on the base of the Holocene deposits are shown in Fig. 4 and when compared with contours on the surface of the chalk trough (Fig. 3) it is clear that a significant sequence of pre-Holocene deposits separate the Holocene barrier-bar sedimentary sequence from the Chalk below. These intervening Pleistocene deposits are dominated by sand and gravel.

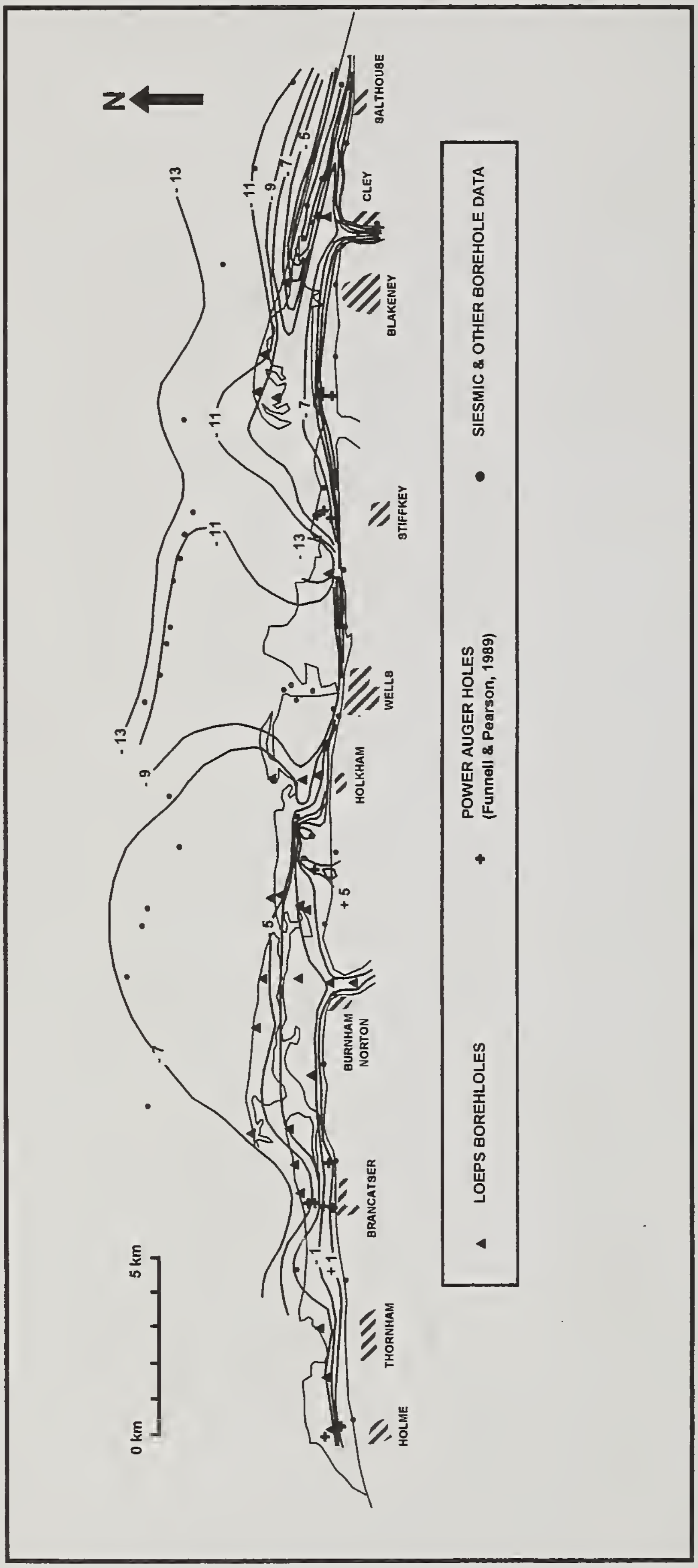


Fig. 4. Contours on the pre-Holocene surface, in metres above Ordnance Datum, of the North Norfolk coast. LOEPS stands for Land-Ocean Evolution Perspective Study (part of the Land Ocean Interaction Study). After Andrews *et al.* (2000).

West of Burnham Norton, the southern margin of the coastal trough extends landward (i.e. south) of the present land-marsh boundary (Fig. 3a). This results in a significant depth of sand and gravel deposits along the coastal margin in this area, with in excess of 17 m observed in places. The sand and gravel deposits that infill the trough along this western section appear to form a continuous lithological unit that extends from the inland Chalk slopes (south of the coastal marshes), beneath the Holocene marsh deposits, and up to the inter-tidal sand flats situated north of the northern margin of the trough.

East of Lady Ann's Drive, Holkham, the Pleistocene sand and gravel unit is restricted to the deepest part of the coastal trough (see lithological logs for cores NNC14, NNC16 and NNC17 in Andrews *et al.*, 2000) with thick Holocene back-barrier deposits tending to directly overlie the Chalk along the marsh-upland boundary. The composition and texture of the sand and gravel deposits in this section of coastline have not yet been described in detail and their lithostratigraphic relationship with the sand and gravel deposits to the west and east is not known.

East of the mouth of the River Stiffkey (Fig. 3b), sand and gravel deposits become more extensive (e.g. at Cley Marshes). Occasionally, sand and gravel deposits, and associated diamicton, protrude through the surrounding Holocene sediments to form small mounds or 'eyes' that are a characteristic feature of this section of the coastal marshes (e.g. Blakeney Eye, NGR TG 040 452; Cley Eye, NGR TG 052 451 and Gramborough Hill, NGR TG 088 442) and foreshore. These sands and gravels are extremely poorly sorted, clast-supported deposits containing a high proportion of large, rounded, predominantly flint pebbles, cobbles and boulders in a fine sand matrix. They are now considered part of the Ringstead Sand and Gravel Member of the Holderness Formation, the diamicton being the Holkham Till Member (BGS 1:10,000 scale map sheet 131: see also Andrews *et al.*, 2002). These deposits contrast markedly with the generally fine-grained sand and gravel deposits characteristic of the western marshes.

In the extreme west of the study area (i.e. west of Holkham), the Holkham Till Member (Holderness Formation) overlies the sand and gravel unit where the trough in the Chalk surface extends inland of the land-marsh boundary. The Holkham Till Member extends from the foot of the till-free Chalk slopes to the feather-edge of the Holocene marsh deposits at the land-marsh boundary. A diamicton present beneath the Holocene deposits in the Land-Ocean Evolution Perspective Study (LOEPS) cores NNC33 and NNC34 (Boomer 1997) is probably also the Holkham Till Member (Andrews *et al.* 2002).

The Pleistocene sands and gravels that infill the trough are generally thought to be glaciofluvial and pilot mineral magnetic data (Andrews *et al.*, 2002) suggest strongly that at least two groups of 'glacial sediment' are present: older Anglian deposits and younger Devensian ones. If correct this implies the trough in the Chalk surface is of pre-Anglian age (see further discussion in Chroston *et al.* 1999; Andrews *et al.* 2002).

Holocene sedimentation and stratigraphy

The complex distribution of modern sedimentary environments and vegetation zones described above represent the youngest Holocene sediments that infill the Chalk trough, and these deposits are repeated throughout the Holocene sequence. The contour map of the pre-Holocene surface based on all the available geological core data (Fig. 4) shows that, in general, the Holocene deposits thicken to the north, away from a feather-edge along the land-marsh boundary at an elevation of approximately +3 m OD. West of Holkham, the Holocene sequence is relatively thin, with a minimum basal elevation of only -5 m OD (suggesting a total depth of ~8 m). East of Lady Ann's Drive, Holkham (approximate NGR TF 892 441) the Holocene sequence deepens substantially, with a minimum basal elevation of -13 m OD (suggesting a total depth of ~16 m). In general the Holocene deposits form a seaward thickening wedge, although at some localities (most notably between Blakeney and Salthouse) they are contained within the pronounced trough structure (Funnell *et al.*, 2000).

Funnell and Pearson (1989) identified nine subsurface Holocene sedimentary units and two 'glacial' units in cores taken from the coastal marshes. This preliminary research was extended by Andrews *et al.* (2000) who identified seven distinct lithofacies with a characteristic composition, depositional mechanism and environment (Table 1). The seven lithofacies were grouped into two key lithofacies associations (LFAs), namely: LFA-A, a predominantly coarse-grained '*barrier*' and tidal channel association; and LFA-B, a predominantly fine-grained '*back-barrier*' mudflat and saltmarsh association. These two lithofacies associations are used in this study as both associations have characteristic hydraulic properties that suggest qualitative hydrogeological classifications for the Holocene deposits (see final column of Table 1).

Table 1. Description of lithofacies within the Holocene deposits of the North Norfolk coast (from Andrews *et al.* 2000)

Lithofacies association	Lithofacies	Description	Depositional environment	Hydrogeological classification*
LFA – B *'Back-barrier'*	LF1 Peat	Black-dark brown humic peats and organic muds	Freshwater swamp to alder carr	AQF or AQT
	LF2 Back-barrier mud & silt	Muds and silts, often laminated	Inter-tidal mudflats, lower and upper saltmarsh	AQT
LFA – A *'Barrier'*	LF3 Muddy sand	Sharp based sand with mud-flakes/pebbles, mud matrix	Tidal channel and creeks	AQT
	LF4 Pebbly sand	Clean sand, scattered pebbles	Exposed, wave influenced environment, washovers	AQF
	LF5 Rooted sand	Vertical rootlets, no pebbles, some mud/sand	Vegetated windblown dunes	AQF
	LF6 Interbedded sand	Thin interlaminated sands, muds	Mixed tidal flat	AQF
	LF7 Gravel	Clast supported gravel with sand matrix	Upper Beach	AQF

* The 'hydrogeological classification' is a qualitative assessment based on sediment lithology where AQF denotes an aquifer and AQT denotes an aquitard.

The detailed stratigraphic relationships between the lithofacies that comprise the North Norfolk Holocene sequence are revealed in eight cross-sections constructed as part of the LOEPS project (Boomer 1997; summarized in Andrews *et al.* 2000). The base of the Holocene sequence is usually marked by a terrestrial freshwater peat that was deposited on the low-lying coastal land surface as it became saturated with freshwater when regional groundwater levels rose in response to Holocene sea-level rise (Andrews *et al.* 2000). The top of this basal peat unit generally marks the change from freshwater to marine conditions, and radiocarbon dates suggest that the marine inundation, and presumably formation of the coastal barrier system, commenced typically between 6 and 7 ka BP (Andrews *et al.*, 2000) at least in the central and eastern parts of the barrier coastal zone. Between the land-marsh boundary and the modern barrier structures, fine-grained back-barrier deposits dominate the

Holocene sequence and overlie the basal peat. Conversely, coarse-grained barrier deposits dominate the Holocene sequence seaward of the barriers.

There appears to be a significant difference in the nature of the back-barrier deposits encountered in the western marshes, compared to those of the eastern marshes. West of Lady Ann's Drive, Holkham, the back-barrier deposits are generally thin and often contain a significant component of LF3 channel sand and gravel (Andrews *et al.*, 2000). In contrast, the back-barrier sediments east of Lady Ann's Drive (Holkham) to Blakeney are dominated by low permeability mud and silt deposits (LF2 of Table 1) with only minor amounts of coarse channel sands. East of Blakeney, the Holocene sequence progressively thins as the pre-Holocene ridge of Chalk that fixes the current position of Blakeney Point spit approaches the land margin and the intervening trough shallows.

Geological subdivision of the coastal zone

From the discussion presented above, it is possible to sub-divide the north Norfolk coastal zone into at least three zones sharing a common geology and hydrogeology. The extent of these three 'geological units' is shown in Fig. 5 and includes:

Geological Unit 1 - Holme to Lady Ann's Drive, Holkham

The Holocene sequence is generally thin with a basal elevation seldom below -6 m OD. Fine-grained inter-tidal mud and saltmarsh back-barrier sediments (LFA-B) dominate the Holocene sequence landward of the present barrier structures but often include a large component of coarser grained inter-tidal channel sand and gravel (i.e. LF 3). The entire Holocene sequence is underlain by a continuous glaciofluvial sand and gravel unit that extends from south of the land-marsh boundary (where it abuts the exposed Chalk slopes) to the inter-tidal sand flats seaward of the barrier structures. The sand and gravel unit can exceed 15 m in thickness where it occurs landward of the land-marsh boundary and is overlain by Holkham Till (south of the feather-edge of the Holocene marsh deposits). The trough in the Chalk surface is generally a subdued feature, seldom being lower than -10 m OD in elevation.

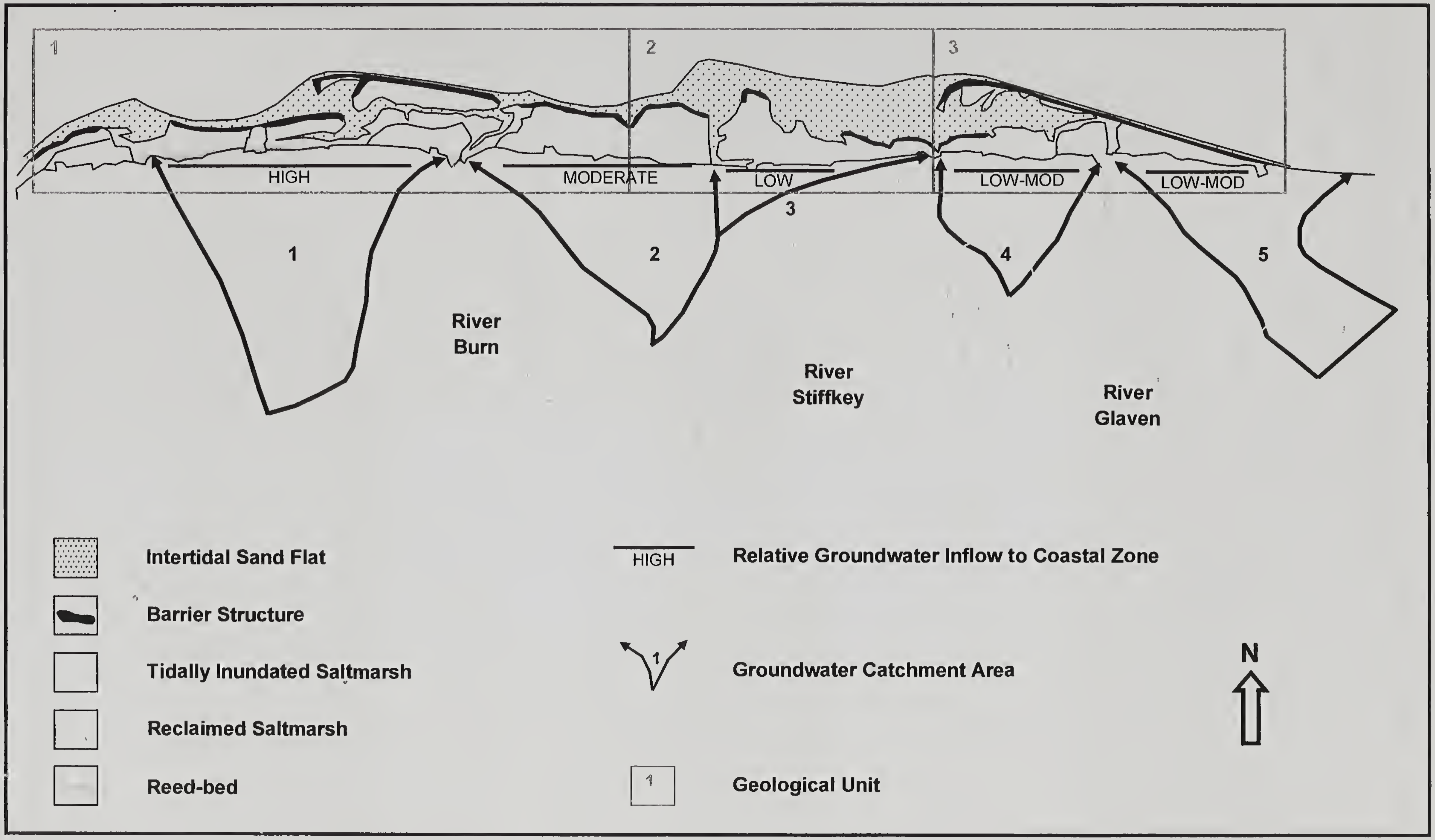


Fig. 5. Geological and hydrogeological subdivision of the barrier coastline of North Norfolk. Groundwater catchment areas 1, 3 and 5 are approximately equivalent to geological unit 1 (groundwater-active), geological unit 2 (groundwater-inactive) and geological unit 3 (reclaimed saltmarsh) areas.

Geological Unit 2 - Holkham (Lady Ann's Drive) to Morston

The Holocene sequence is deep with a basal elevation that can be below -10 m OD. Fine-grained inter-tidal mud and saltmarsh deposits dominate the subsurface Holocene sequence found landward of the barrier structures, with little channel sands and gravels. At the land-marsh boundary the Holocene marsh deposits (LFA-B) directly overlie the Chalk aquifer, although glacio-fluvial sand and gravel is observed below the Holocene deposits beneath the deepest part of the Chalk trough (e.g. Holkham and Warham). The trough in the Chalk surface is deep along this section, with a minimum basal elevation along its axis below -15 m OD.

Geological Unit 3 - Morston to Weybourne

The Holocene sequence is generally deep with a basal elevation that can exceed -7 m OD. A glaciofluvial sand and gravel unit is present beneath the Holocene sequence and extends up to the land-marsh boundary where it directly overlies the Chalk. East of Blakeney, Holocene and pre-Holocene deposits are contained within a well-defined trough, with a northern (seaward) boundary delimited by Blakeney Point Spit. The trough is a deep structure with a basal elevation below -14 m OD, although it shallows towards Weybourne in the west where the trough narrows. The majority of the land area within this section is composed of non-tidal reclaimed saltmarsh that comprises Blakeney Freshes and Cley-Salthouse marshes.

Using existing geological information presented above and new data obtained from a network of installed boreholes and piezometers, installed as part of this research it was possible to construct geological cross-sections for the three representative geological units along the coastline presented in Fig. 6. The full geological and constructional logs for the new boreholes and piezometers used to produce the cross-sections in Fig. 6 are provided in Appendices 3 and 4.

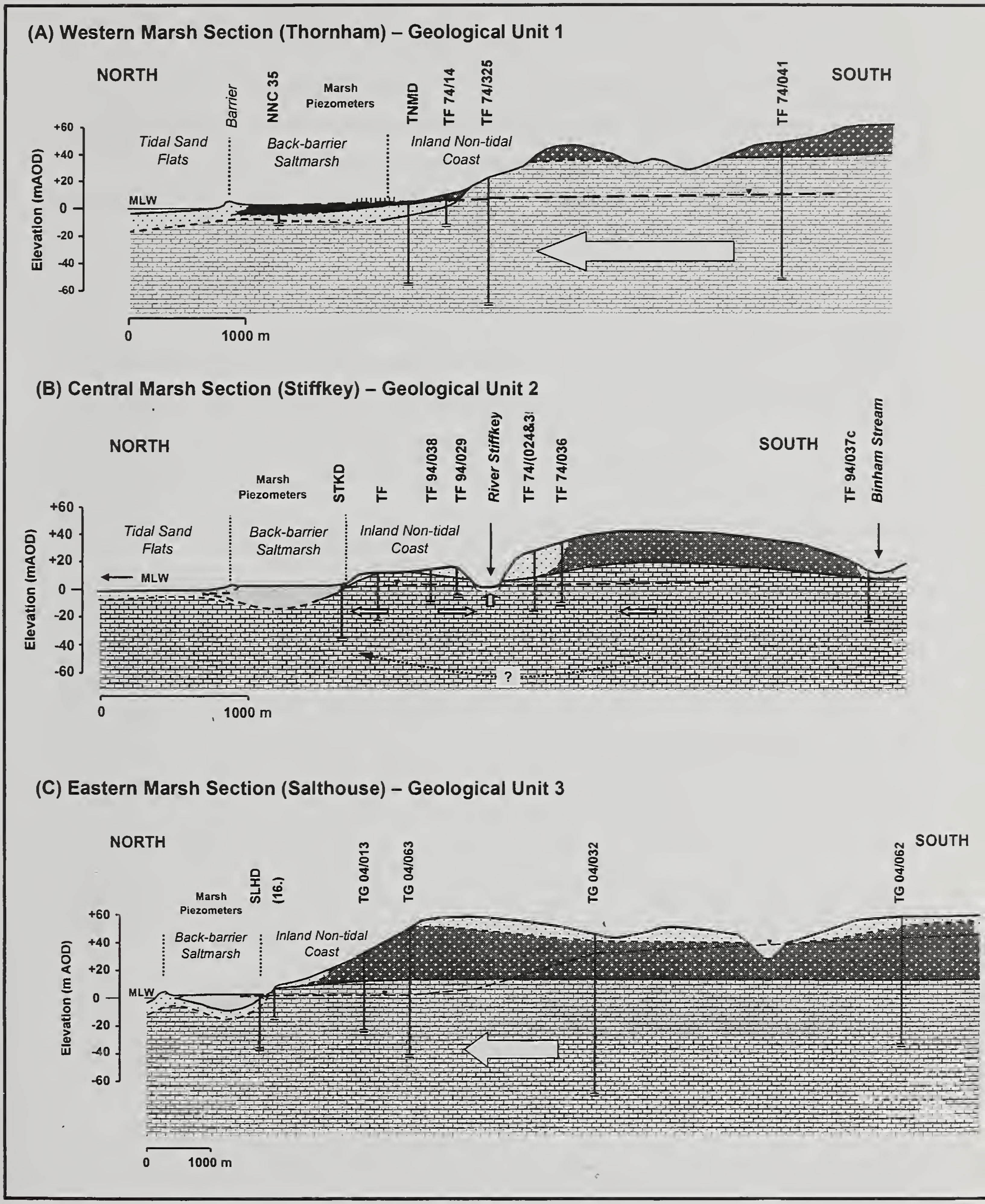


Fig. 6. Geological cross-sections for the principal 'geological units' identified along the barrier coastline of North Norfolk.

HYDROGEOLOGY OF THE COASTAL ZONE

Relative groundwater influx to the North Norfolk coast

By a simple consideration of inland groundwater catchment characteristics, a qualitative prediction of the relative significance of groundwater discharge along different sections of the North Norfolk coast can be made. When combined with the geological subdivisions of the coastal zone identified previously (see Figs 5 and 6), it is possible to subdivide the study area into zones likely to share a similar hydrogeology.

The inland groundwater catchment characteristics most relevant to such a qualitative assessment are the groundwater catchment area and catchment geology. Other factors, such as aquifer permeability and the degree of groundwater utilisation (e.g. by abstraction) are also important but their omission does not compromise this simple qualitative assessment.

Groundwater catchment areas have been defined by groundwater contours for the Chalk aquifer by ENTEC UK Ltd. (2003) and represent the total area of aquifer draining to a specific section of the coastline. Five groundwater catchment areas of varying size drain the Chalk aquifer to the North Norfolk barrier coastline as shown in Fig. 5.

Inland catchment geology is extremely important in determining the groundwater flux to the coast as it exerts a primary control on the effective recharge to the Chalk aquifer, assuming a single net precipitation across the entire study area. This is a reasonable assumption considering the comparatively small size of the area. In North Norfolk, the magnitude of effective recharge is strongly affected by the hydraulic properties of the glacial deposits that overlie the Chalk. Although the glacial deposits of North Norfolk are inherently heterogeneous in nature, broad assumptions regarding their overall properties can be made and a qualitative classification of relative recharge attempted by considering the composition, thickness and spatial distribution of glacial deposits overlying each groundwater catchment area.

Using a simple qualitative matrix to combine these two catchment characteristics, Green (2004) predicted the relative groundwater influx to the North Norfolk coastal zone. This assessment, summarised in Table 2, suggests a high potential groundwater influx to the coastal marshes along the western half of the study area (west of the River Burn) and a low to moderate potential influx to the coastal zone in the east (Wells-next-the-Sea to Salthouse).

Table 2. Qualitative assessment of the relative flux of groundwater to the coast for each groundwater catchment area defined in Fig. 5

GROUNDWATER CATCHMENT AREA[*1]	CATCHMENT AREA		CATCHMENT GEOLOGY			Relative flux of groundwater to the coastal zone[*3]
	≈ km^2	Classification	Area covered[*2] (%)	Description	Recharge classification	
1	*60*	*LARGE*	*LOW-MOD*	*Thin, sandy till*	*HIGH*	***HIGH***
2	*15*	*SMALL – MODERATE*	*MODERATE*	*Till*	*MODERATE*	***MODERATE***
3	*7*	*SMALL*	*MODERATE*	*Till*	*MODERATE*	***LOW-MODERATE***
4	*15*	*SMALL – MODERATE*	*HIGH*	*Till*	*LOW – MODERATE*	***LOW – MODERATE***
5	*35*	*MODERATE*	*HIGH*	*Thick till*	*LOW*	***LOW – MODERATE***

*1 Groundwater catchment area reference number refers to Fig. 5
*2 Relative proportion of catchment area covered by Quaternary till deposits
*3 Relative flux of groundwater to the North Norfolk coast estimated by Green (2004)

Hydrogeological features of the North Norfolk coast

To aid the hydrogeological conceptualisation of the North Norfolk coastal zone, two surveys of hydrogeological features were undertaken within sections of natural, tidally-inundated marsh. Reclaimed marshes were not surveyed as high water levels and significant sedimentation within the creek systems tend to obscure most features indicative of groundwater-surface interaction. To validate the qualitative assessment described above, the two survey areas were selected within areas of saltmarsh with the greatest contrast in relative groundwater activity (as presented in Table 2 above) and should reflect the likely diversity of hydrogeological features within the entire tidal marsh system.

Survey Section 1 was situated in the 'Holme to Holkham' geological unit 1 with a high relative groundwater influx (Fig. 5). In contrast, Survey Section 2 was situated in the 'Holkham to Morston' geological unit 2 in an area of low relative groundwater influx (Fig. 5). Survey Sections 1 and 2 constitute approximately 50% and 40% of their geological unit lengths, respectively.

Survey Section 1: Thornham to Burnham Norton

The hydrogeological features evident within these western marshes include marginal groundwater seepage, discrete groundwater springs and groundwater-fed, non-tidal marsh drains. Other, indirect indicators of freshwater activity are also observed, primarily the occurrence of extensive *Phragmites* reed beds across tidal, upper marsh along the land-marsh

boundary. The large number of features of groundwater-surface interaction is consistent with the high groundwater inflow predicted for this section of coastline.

Groundwater spring discharges

A characteristic feature of the western marshes is the common occurrence of discrete spring discharges within the creek system that are exposed during ebb-tide drainage. These springs can be qualitatively divided into at least three 'types' on the basis of their appearance and apparent discharge rate:

- *'Large' springs* (Fig 7a-b): generally 1 to 2 m in diameter, situated in the bottom of marsh creeks, often with a substantial 'horseshoe' of inter-tidal marsh mud developed around the point of discharge. Some large springs are turbulent and sandy in nature (Fig 7a). Alternatively they can occur as large still pools of water (Fig 7b). Large springs have an obvious outlet channel exhibiting 'significant' flow and in some circumstances they have both an inlet and an outlet channel, with the outlet channel demonstrating noticeably greater flow (Fig 7b).

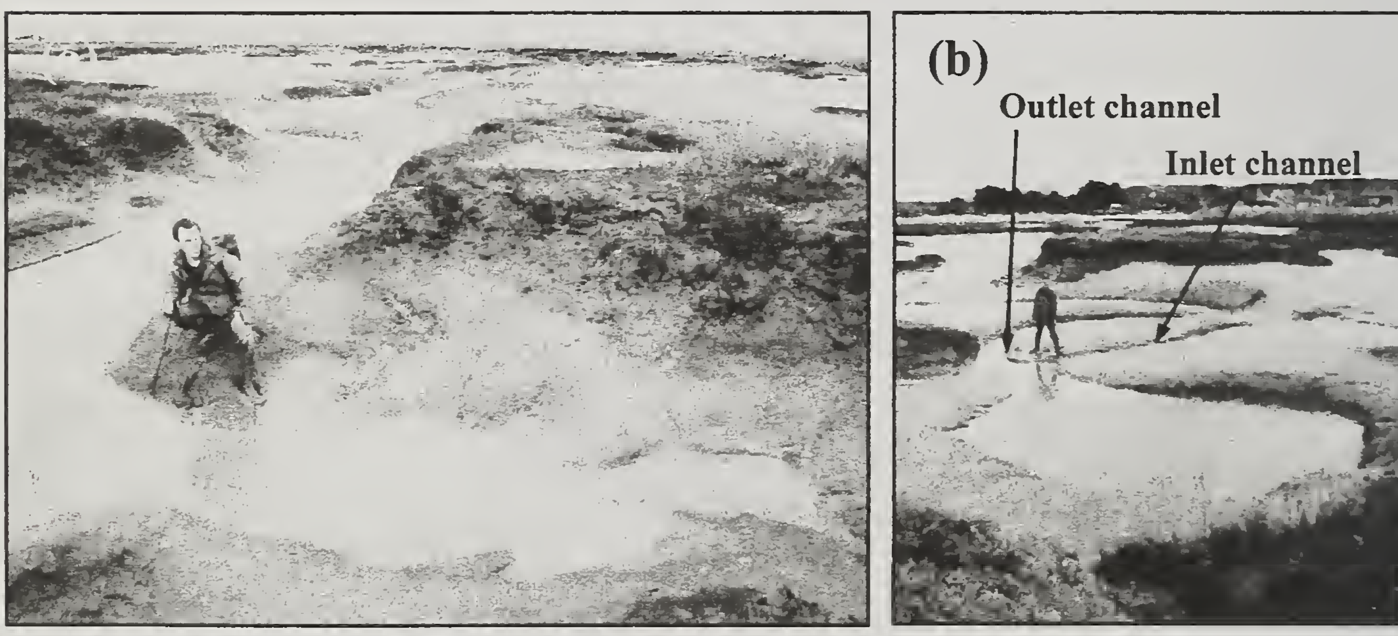


Fig. 7a & b. Large springs in groundwater-active saltmarsh at Brancaster, near Brancaster Staithe Harbour.

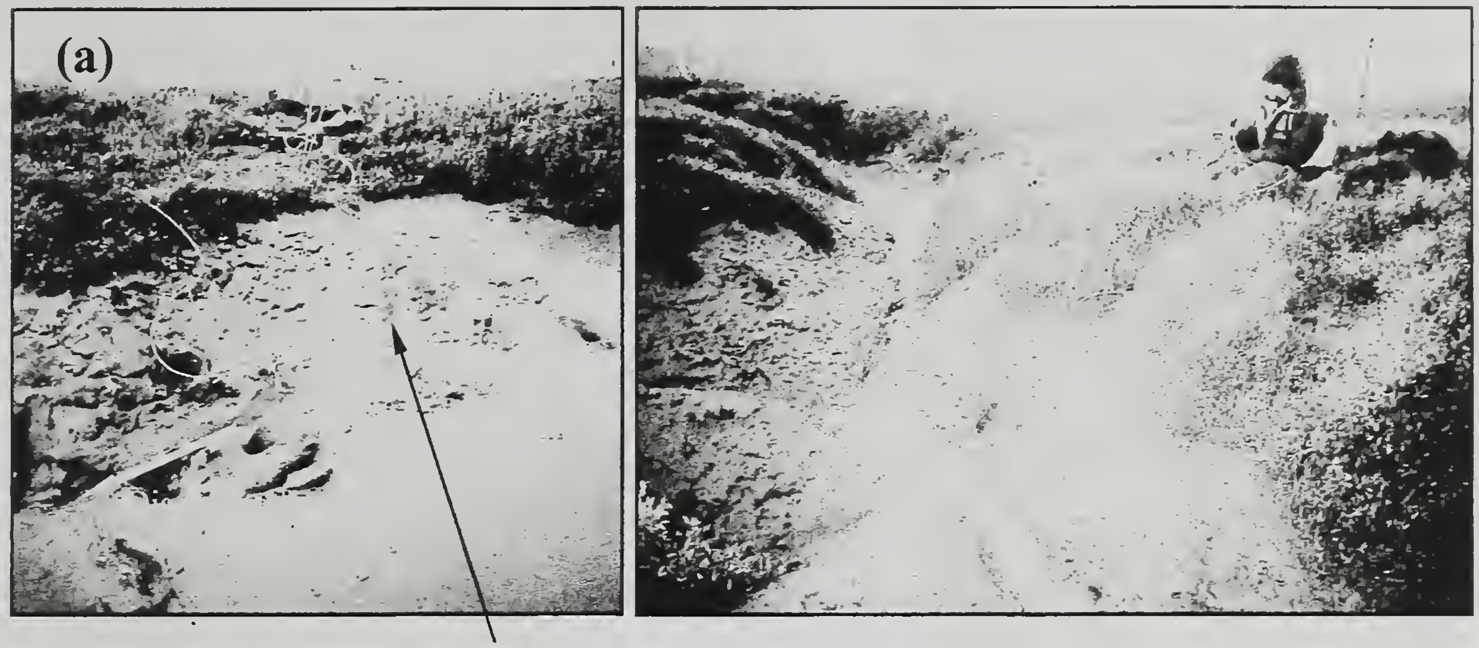


Fig. 8a & b. Creek bottom springs in groundwater-active saltmarsh at (a) Thornham Harbour and (b) Brancaster Marsh.

- *Creek bottom springs* (Fig 8a-b): More common than large springs, with a considerably smaller discharge and size (generally <1 m in diameter). Creek bottom springs generally have a defined outlet channel, but are not always associated with the development of an inter-tidal mud 'horseshoe', and can be found in the beds of major creeks dominated by sand material or minor creeks with a preponderance of fine-grained back-barrier material.
- *Small springs* (Fig 9a-b): Minor spring seepage, generally located at the bottom of incised creek banks emanating from either muddy or sandy deposits. They can be located at a considerable distance from the land-marsh boundary and seldom have a defined outlet channel.

Both 'large springs' and 'creek bottom springs' appear to be fixed points of perennial groundwater discharge within the coastal zone, where the rate of groundwater discharge is sufficient to prevent infilling of the spring discharge point (the 'spring-head') by fine-grained tidal sediment. At some localities, spring-like features are observed that have been completely infilled with tidal mud. When excavated, minor seepage is sometimes found in

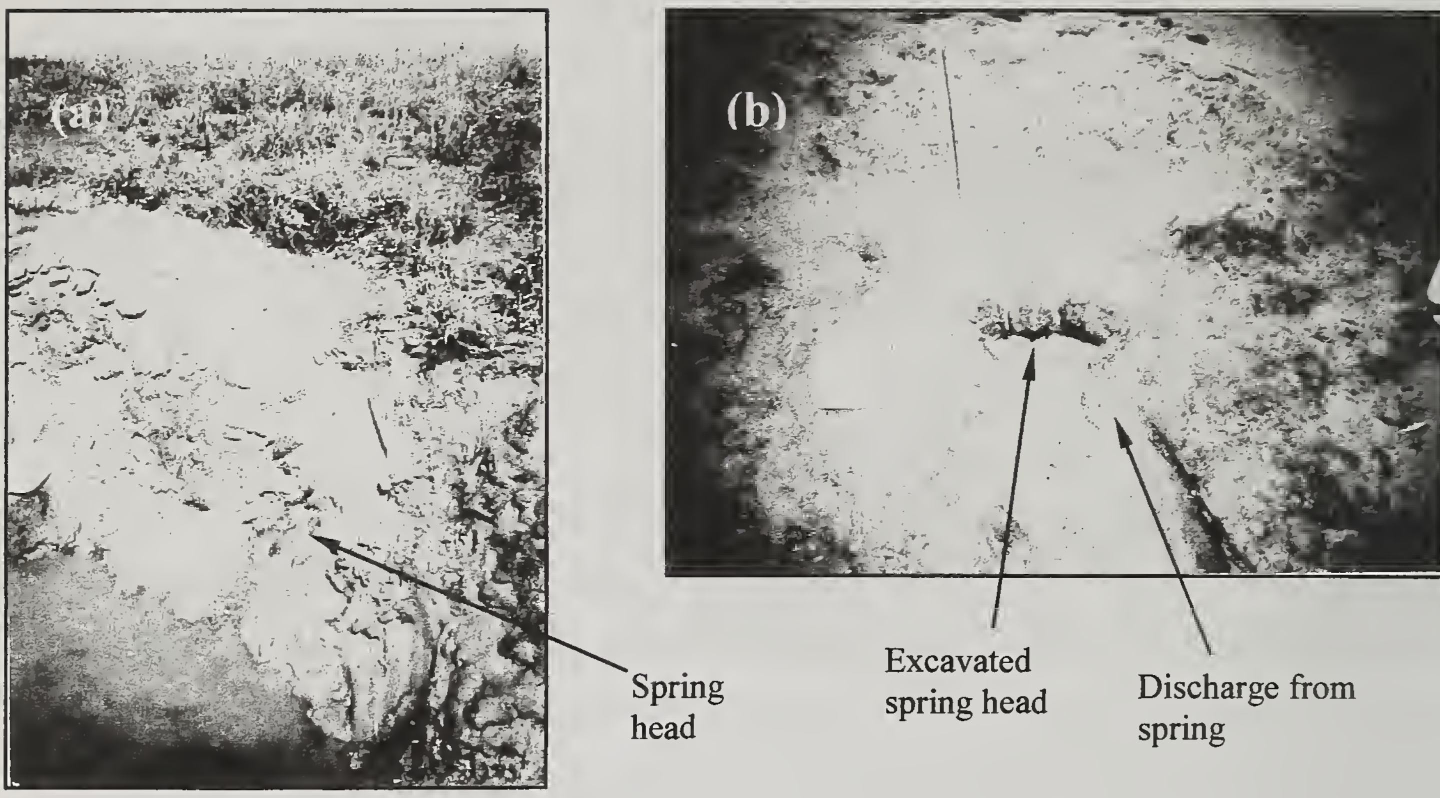


Fig. 9a & b. Minor springs in groundwater-active saltmarsh in (a) Brancaster Marsh and marshes between Titchwell bird reserve and (b) Brancaster.

these structures, indicating that they may be a point of minor spring discharge where the groundwater flux is insufficient to flush the influent tidal sediment.

A number of the 'small springs' could not be relocated on repeat visits to the coastal marshes, demonstrating that not all small springs are perennial features. This is unsurprising considering the small discharge rate and their location at large distances from the land-marsh boundary where the coastal environment is considerably more dynamic as a result of increased exposure to the tidal and wave action of the sea.

The majority of springs occur within 350 m of the land-marsh boundary, although some are found at distances exceeding 500 m. Significantly, most springs tend to occur in distinct zones separated by areas of tidal marsh largely devoid of any observable evidence of direct groundwater activity.

Groundwater seepage

Groundwater is observed to enter the creek system through marginal seepages along the land-marsh boundary. Groundwater seepage can be observed directly as either significant diffuse flow emanating from exposed marginal sand and gravel deposits (Fig. 10a) or as more chaotic discharge from an area where a thin veneer of inter-tidal mud overlies the sand and gravel (Fig. 10b). Alternatively, seepage is observed indirectly by the occurrence of

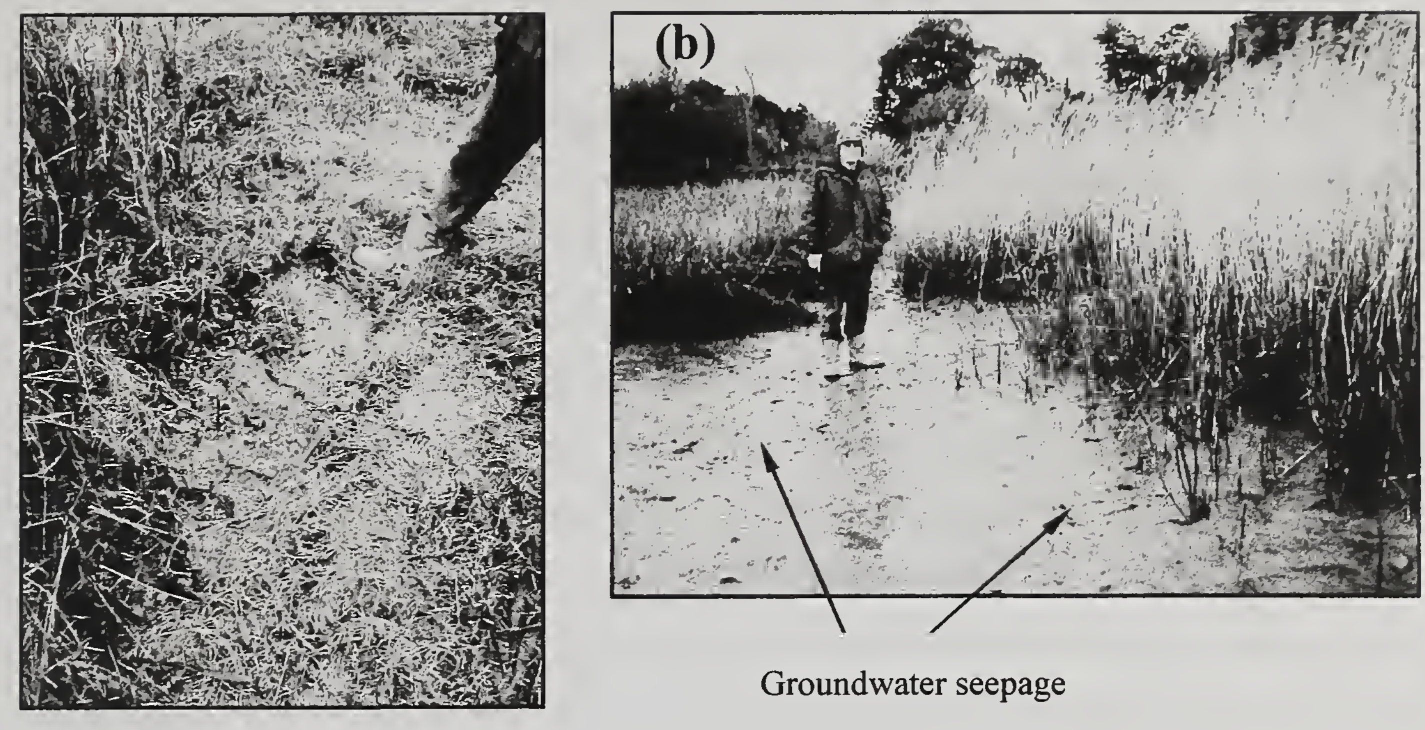


Fig. 10a & b. Groundwater seepage from the land-marsh boundary of the groundwater-active saltmarsh. Groundwater seepage is observed either (a) direct from the marginal sand and gravel deposits, or (b) through a thin veneer of Holocene back-barrier mud at the land-marsh boundary.

---

localised areas of saturated marsh surface at the land-marsh boundary or as non-tidal land drains which exhibit an observable accretion of flow along their length before entering the tidal marsh system. In some circumstances, minor spring discharges were also observed in high-permeability sediments forming the base of non-tidal land drains.

The diffuse seepage of groundwater directly to the base of tidal creeks could not be observed within the tidal marshes directly, although many creeks within the western marshes do have a bed composed of sandy deposits (e.g. Mow Creek, Brancaster) or a coarse bed material composed of shelly material (e.g. Thornham and Brancaster Staithe). It should be noted that points of discrete spring discharge were also found in creek bottoms characterised by such coarse material, reinforcing the idea that these processes may constitute two very different discharge mechanisms within the coastal marshes of North Norfolk.

A key feature of the hydrogeology of the groundwater-active saltmarshes in North Norfolk is the heterogeneous distribution of the features of groundwater discharge across the coastal zone, both laterally along the coastline and perpendicular to the land-marsh boundary. This produces a 'zoned' distribution where localised areas of intense spring activity are often separated by areas of saltmarsh devoid of any obvious signs of groundwater activity.

Survey Section 2: Wells-next-the-Sea to Stiffkey Outfall

In contrast to the western, groundwater-active saltmarsh survey area, this section is characterised by an absence of identifiable hydrogeological features within the marsh system. Only a limited number of springs were observed in a major creek located at the land-marsh boundary (i.e. Garborough Creek, NGR TF 970 440). The major freshwater influence on these marshes appears to be the outfall of the River Stiffkey in the east. The occurrence of spring discharge from sand and gravel deposits to the small 'tributary stream' flowing northwest and discharging to the coastal marshes in the vicinity of Wells-next-the Sea has been reported, although its presence was not confirmed during this study.

Salinity variations within the creek system of the North Norfolk coastal zone

Tidal cycle chloride survey

The high degree of groundwater activity observed at certain localities within the coastal zone and the prolonged period of ebb-tide drainage suggests that the chloride concentration of water discharging from the creek system may give a qualitative indication of the 'freshwater' input to the coastal system of North Norfolk. Where sources of surface water input are known, this simple parameter may indicate the degree of groundwater-surface interaction within the coastal zone. To test this hypothesis, water level measurements and water samples were taken at approximately hourly intervals from a number of creeks over a complete tidal cycle at two localities within the coastal marsh system. The chloride concentration of each water sample was determined in the laboratory by titration with silver nitrate.

Thornham Harbour (NGR TF 727 442)

Five creeks were sampled at Thornham Harbour (see Fig. 11), each of which had unique hydrological and hydrogeological characteristics as described below:

TH1 Main estuary creek at Thornham Harbour, draining a large area of saltmarsh with considerable groundwater activity (i.e. springs) and some land drains along the land-marsh boundary.

TH2 A tributary to the main creek, draining an area of groundwater-active saltmarsh and including discharge from some land drains at the land-marsh boundary.

TH3 A tributary to the main creek, draining an area of groundwater-active saltmarsh with no other obvious sources of freshwater input.

TH4 A minor creek draining a small area of saltmarsh with little observable surface groundwater activity.

TH5 Creek situated immediately downstream of the tidal sluice gate controlling discharge from the River Hun.

Considering the close proximity between each water sampling point, the water level within the creek system was measured at a single intermediate location. As described earlier, the tidal regime is characterised by a rapid flood-ebb tidal surge of approximately 1.5 m, followed by a long period of ebb-tide drainage during which water levels are low and vary little. A significant flow of water with minimal turbidity was observed at TH1, TH2 and TH3 throughout ebb-tide drainage. This contrasts with the low volume of water, with a large suspended sediment load, draining from the marsh showing little freshwater activity at TH4.

The results of the tidal cycle chloride survey are shown in Fig. 11. The trend in chloride concentration measured in water samples from TH1, TH2, TH3 and TH5 are dominated by a low concentration ($Cl^- < 1500$ mg l^{-1}) attained rapidly after the flood-ebb tidal surge, but rising to approximately 16,000 mg l^{-1} at high tide. In contrast, TH4 is characterised by a high chloride concentration ($Cl^- > 14,200$ mg l^{-1}) throughout the tidal cycle, with a maximum concentration observed at high tide of approximately 16,000 mg l^{-1}, equivalent to that measured within the other creeks. The lowest chloride concentrations of approximately 240 mg l^{-1} occur in the creek situated immediately downstream of the tidal outlet of the River Hun (TH5), where the flow rate is substantial at low tide. The time lag between the rise in tide level and rise in chloride concentration observed at TH3 and TH5 reflects the higher elevation of the creeks at these sampling localities.

Stiffkey Marshes (NGR TF 964 443)

The results of the second tidal cycle chloride survey undertaken within the eastern marshes at Stiffkey are presented in Fig. 12. The water level in the creek system was measured at the footbridge indicated on the schematic site plan. No change in water level was observed at this point due to a low neap tide at the time of the survey. A minor flood-ebb surge was observed, however, at the most seaward sample point within the main creek (SP1) and this point is used to define the approximate time for high tide to occur during the flood-ebb surge shown in Fig. 12.

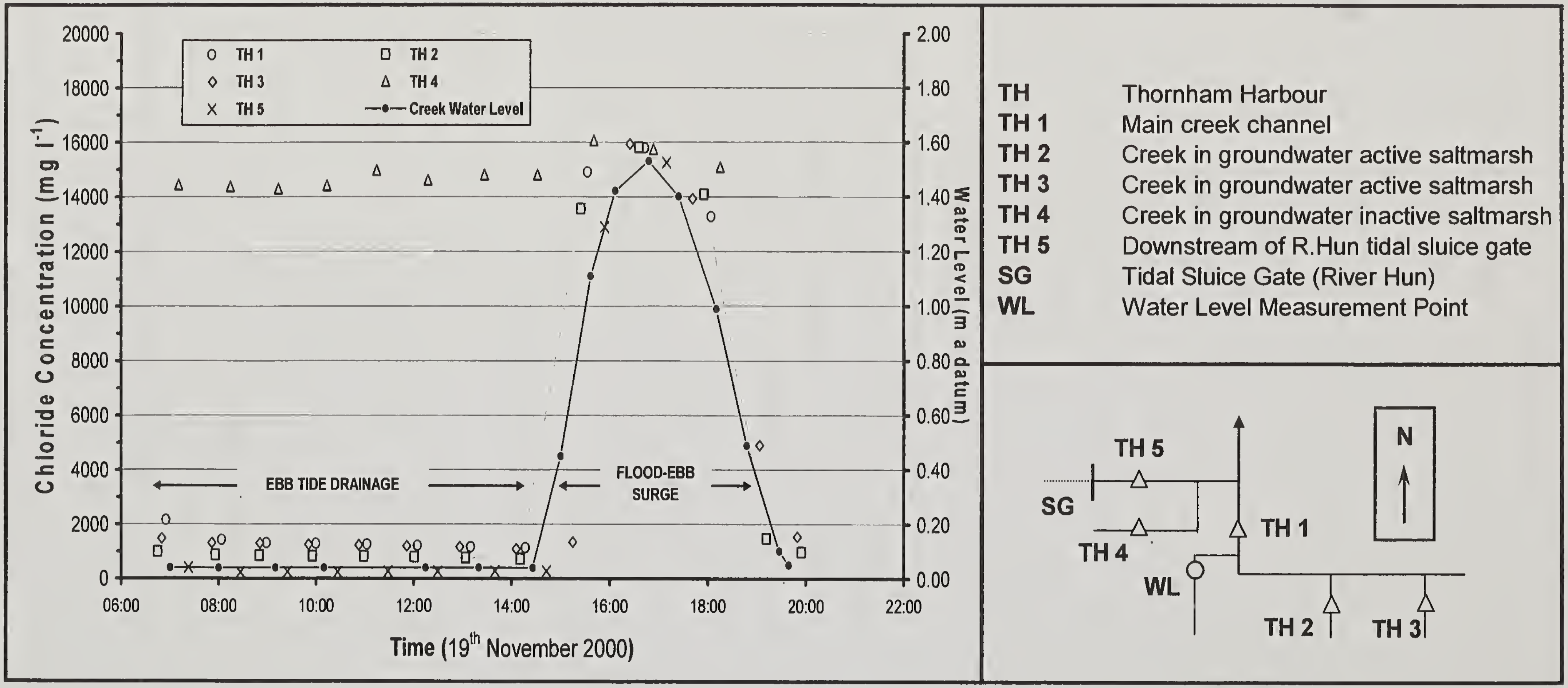


Fig. 11. Results of the tidal cycle chloride survey at Thornham Harbour (NGR TF 727 442) within an area of groundwater-active saltmarsh, on 19 November 2000.

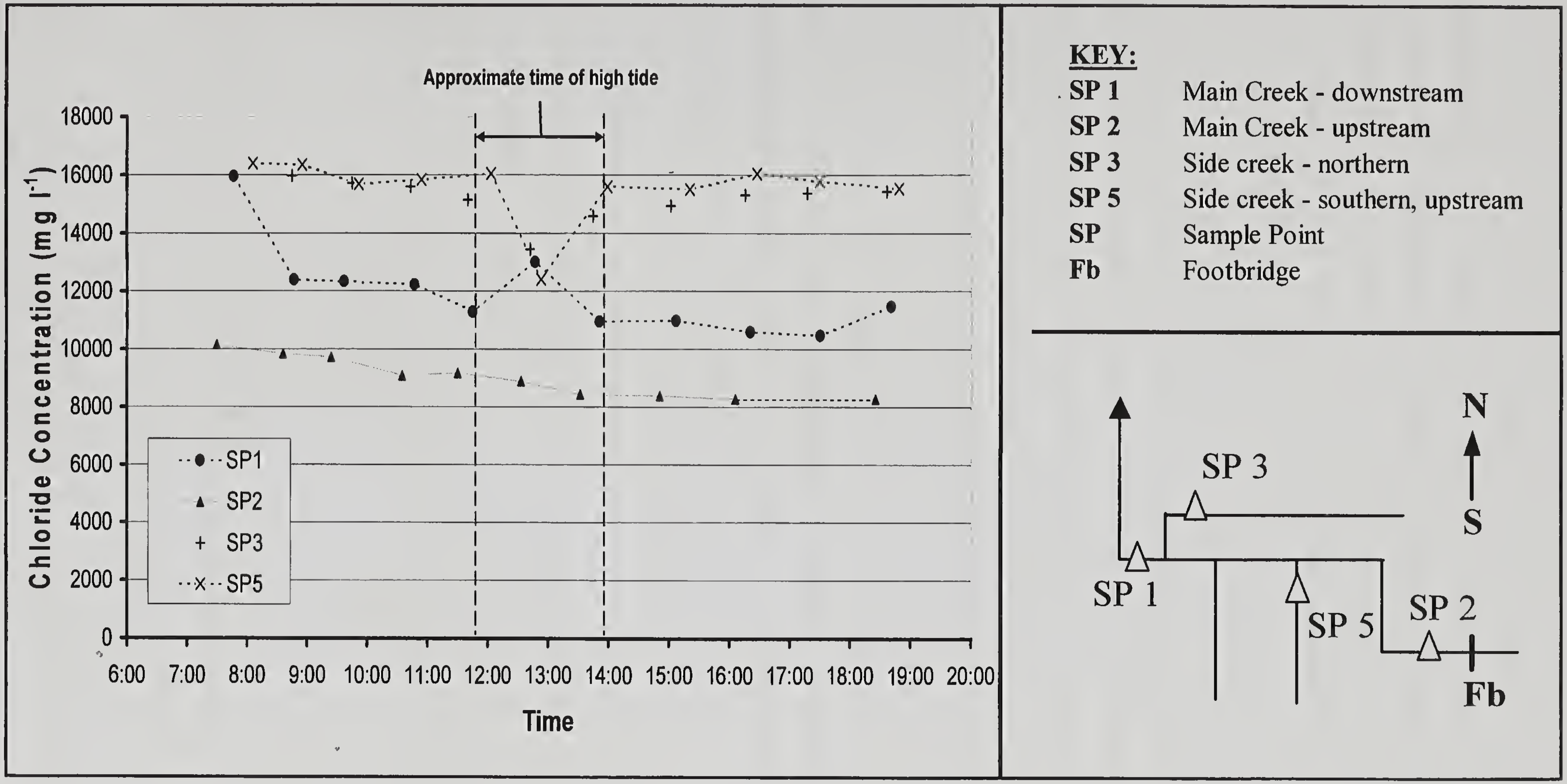


Fig. 12. Results of the tidal cycle chloride survey at Stiffkey Marshes (NGR TF 965 439) within an area of groundwater-inactive saltmarsh, in November 2000.

The most seaward sample site on the main creek channel (SP1) shows a 'typical', albeit subdued, trend in chloride concentration resulting from the inundation of high salinity seawater over the flood-ebb tidal cycle. The chloride concentration measured in samples taken from SP2 (upstream in the main creek) is significantly less than that measured at all other sample points as it receives groundwater from the minor springs identified in Garborough Creek. No change in the creek water level is observed at SP2 and consequently the chloride concentration shows a continual decline over the entire tidal period as seawater drains and the significance of the freshwater input to the main creek becomes progressively greater relative to the total outflow from the creek. The anomalous decrease in chloride concentration observed at SP3 and SP5 at the time of the flood-ebb surge may result from the backing-up of the lower-salinity water contained within the main channel (as seen at SP2), thus diluting the higher salinity water draining from these tributary creeks.

Generally, chloride concentrations measured within the Stiffkey creek system were high, being comparable to the concentrations measured in the groundwater-inactive creek at Thornham Harbour (point TH4). These high chloride concentrations represent a minimum concentration that can be expected within the creek system because the absence of a flood-ebb surge at most sample points allowed the discharge of the tidally-inundated seawater for two complete tide cycles, thus any freshwater component will be of greater relative significance to the total outflow from the creek system.

From both tidal cycle surveys it is apparent that the chloride concentration in water discharging from the North Norfolk coastal creek system covers the complete range from essentially fresh ($Cl^- < 250$ mg l^{-1}) to seawater ($Cl^- \approx 18{,}000$ mg l^{-1}). Furthermore, the unique tidal regime affecting this coastline results in a tendency for creek water discharged during ebb-tide drainage to be dominated by either seawater or freshwater depending on the degree of groundwater or surface water input to the system. This suggests that a simple survey of chloride concentrations within the tidal creek system over the ebb-tide is a valid method for identifying areas of coastal marsh receiving a significant contribution of freshwater input and even groundwater input when combined with other field observations of surface water input.

<u>*Ebb-Tide creek chloride survey*</u>

In light of the results from the tidal cycle chloride survey, an additional spatial survey of chloride concentration in water discharging from the creek system during ebb-tide drainage was undertaken along the same coastal sections. The measured chloride concentrations were then used to subdivide the marsh system into two broad 'salinity' groups to identify those creeks with a large freshwater influence ($Cl^- < 2000$ mg l^{-1} during ebb-tide drainage). To save time, the second survey in the eastern marshes also utilised electrical conductivity measurements as a measure of salinity.

As Fig. 13 demonstrates, the creeks draining the western coastal marshes have a strong freshwater influence with many creeks exhibiting chloride concentrations below 3500 mg l^{-1} during ebb-tide drainage. The location of the low salinity creeks shows a strong correlation with the zones of high groundwater activity, although some low-salinity creeks do receive a contribution of freshwater from other sources, most notably outflow from the tidal sluices on reclaimed marsh and/or non-tidal drains, as well as the groundwater input identified. In groundwater-active areas, the high tidal range results in some creeks draining virtually only freshwater over the ebb cycle. A simple, two-member conservative mixing calculation for chloride at the Thornham study site indicates that the water draining from the coastal marshes may potentially be composed of approximately 95% fresh groundwater (assuming $Cl^-_{seawater} \approx 18{,}000$ mg l^{-1} and $Cl^-_{groundwater} \approx 50$ mg l^{-1}).

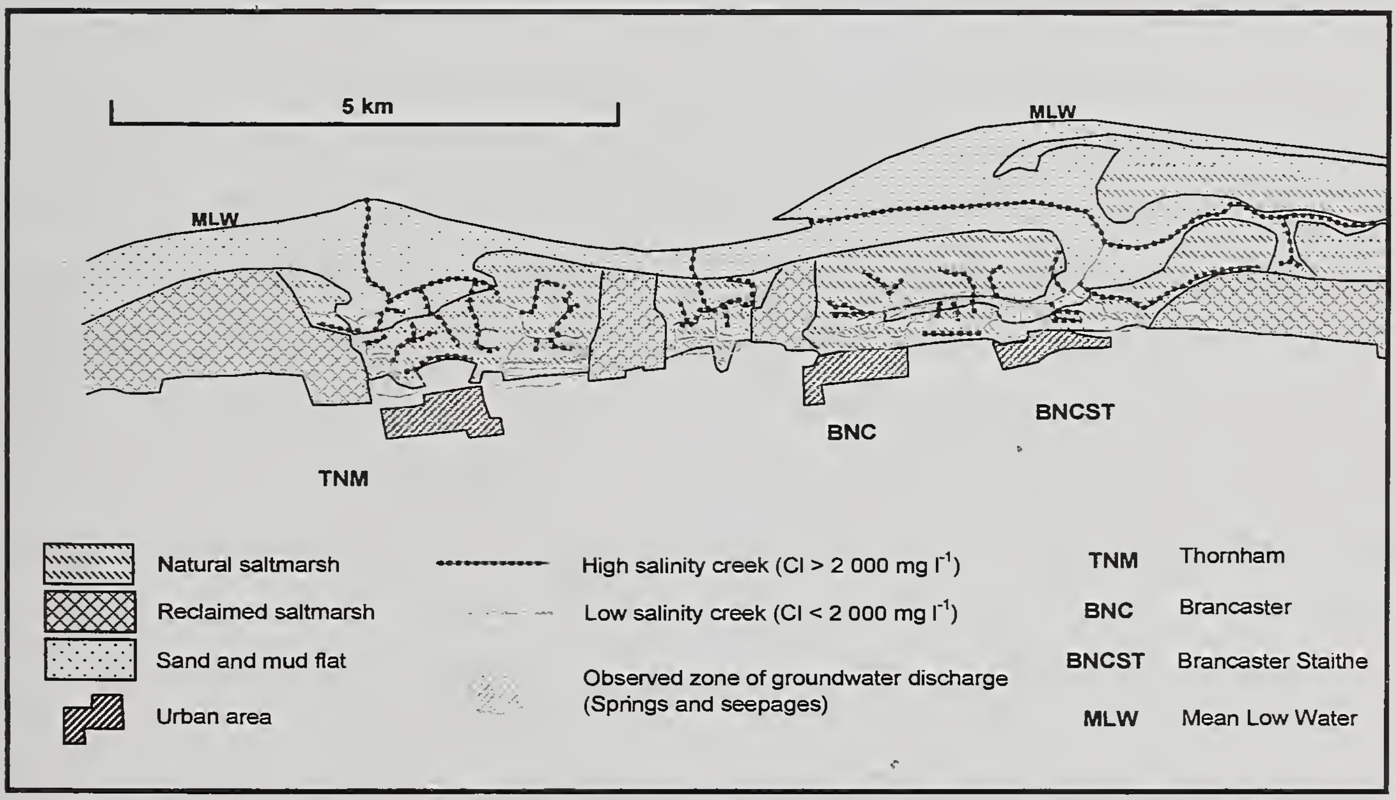


Fig. 13. Results from field reconnaissance and ebb-tide creek chloride survey in the coastal marshes of northwest Norfolk.

This figure of 95% fresh groundwater is a maximum contribution as the creeks will also receive a component of brackish marsh porewater from lateral drainage through creek banks.

In contrast, creeks draining the eastern marsh system are dominated by high salinities approaching that of seawater, with an electrical conductivity exceeding 55 mS cm^{-1} in almost all samples. This observation implies a limited degree of freshwater influence to these marshes from the inland Chalk aquifer. The only creeks between Wells and the Stiffkey outfall that show any influence of freshwater are situated in the immediate vicinity of the outfall, possibly demonstrating the effect of groundwater flow, and hence discharge concentration in this area, and in Garborough Creek, the site of two springs identified during field reconnaissance.

Salinity transect across the groundwater-active section of the coastal zone

To better understand the influence of fresh groundwater within groundwater-active areas of the North Norfolk coastal zone, a transect of chloride concentration measurements was undertaken from the network of boreholes, saltmarsh piezometers and sand-flat piezometers (seaward of the present barrier structure) installed at Thornham (see transect A-A' Fig. A1.1b in Appendix 1). Chloride concentrations were combined with geological data (see Appendices 3 and 4) and groundwater level measurements to construct Fig. 14.

The groundwater potentiometric surface shown in Fig. 14 emphasises the potential for upward groundwater flow from the Chalk and pre-Holocene sand and gravel aquifer confined below the overlying Holocene marsh deposits, to the overlying tidal creek system. All water samples taken from the piezometers and boreholes that penetrate the sand and gravel unit overlying the Chalk demonstrated that this unit is saturated with freshwater, even at considerable distances from the land-marsh boundary (e.g. Cl < 60 mg l^{-1} in the deepest piezometer within the central marsh piezometer nest, 250 m from the land-marsh boundary). Chloride concentrations increased from the base of the low-permeability back-barrier sediments towards the saltmarsh surface, reflecting the increasing influence of tidal sea water on the upper saltmarsh.

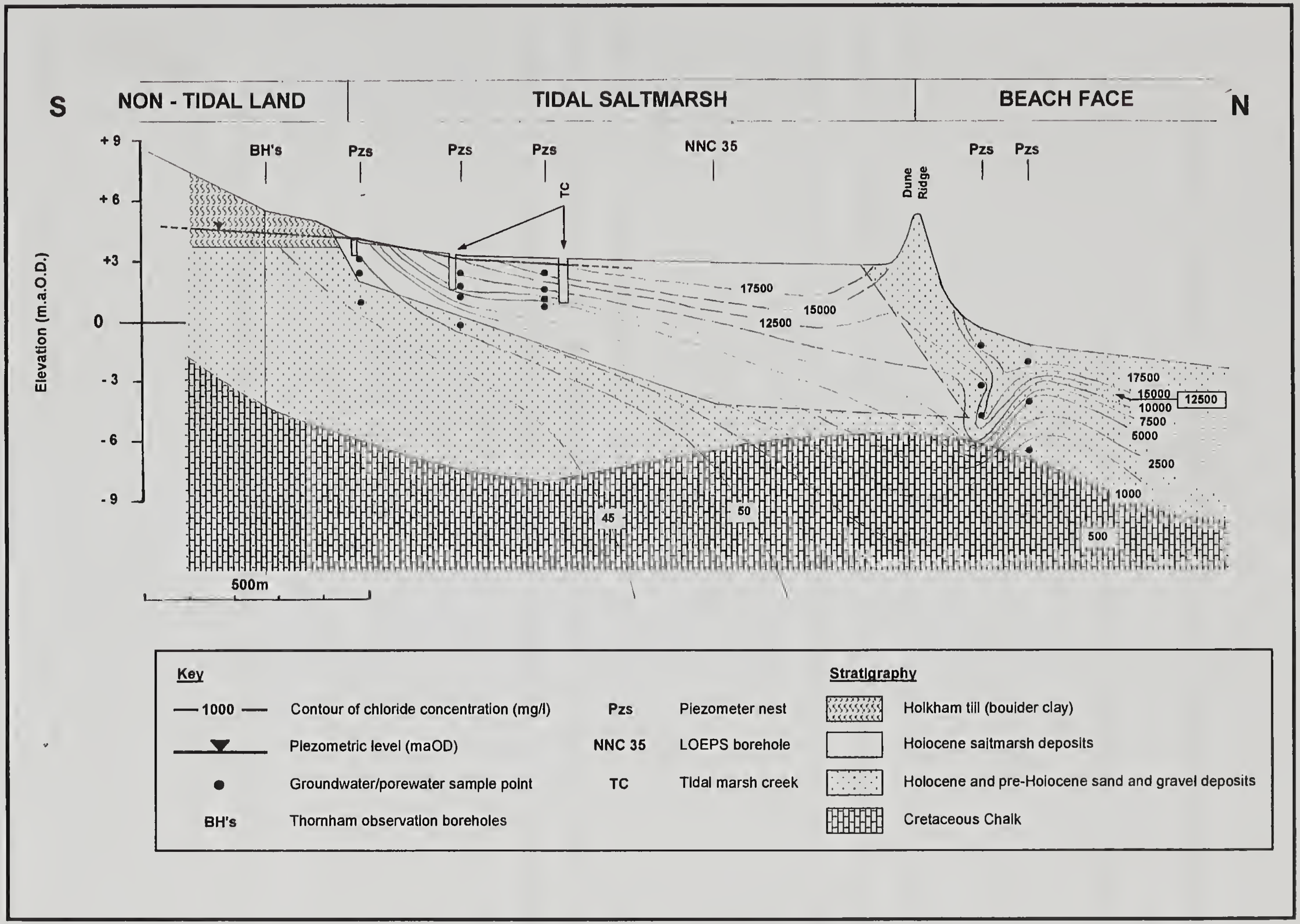


Fig. 14. Stratigraphic and hydrogeological cross-section through the coastal zone at the groundwater-active marsh study site (Thornham), with contours of equal chloride concentration (isochlors given in mg l^{-1}). Transect follows line A-A' in Fig. A1.1b in Appendix 1.

The most striking feature in Fig. 14 is the occurrence of groundwater with a low chloride concentration ($Cl^- < 2000$ mg l^{-1}) at the deepest piezometer of the northern (i.e. seaward) beach piezometer nest. Above this sample point the chloride concentration increases rapidly to near-seawater concentrations (c. 18,000 mg l^{-1}) at the beach surface. The northern (seaward) beach piezometer nest is submerged beneath the sea for the majority of each tide cycle, as the elevation of the beach at this point is only -1.2 m OD. This suggests that the observed freshening at depth is not attributable to an anomalous infiltration of surface freshwater. It seems unlikely that these low chloride concentrations can be attributed to discharge from a local freshwater lens within the adjacent dune ridge as this is not consistent with the vertical chloride profile observed at the southern beach piezometers (i.e. the minor freshening of beach porewater indicated by the mid-depth piezometer) and the overall degree of freshening observed (approximately 90% groundwater, assuming conservative mixing of groundwater, $Cl^- = 50$ mg l^{-1}, and seawater, $Cl^- = 18{,}000$ mg l^{-1}). The most plausible explanation for the distribution of chloride concentrations observed across the beach face involves: (i) a near-surface beach porewater dominated by the intrusion of tidal seawater; (ii) a minor low-salinity lens beneath the dune that mixes with the adjacent, seawater-dominated, near-surface porewater; and (iii) a component of underflow of low-salinity groundwater from beneath the confining marsh deposits to the south, that mixes with the overlying higher salinity water (both (i) and (ii)). Clearly Figure 14 provides good evidence for submarine groundwater discharge from the Chalk aquifer directly to the sea for the Thornham groundwater-active coastal marsh.

CONCEPTUAL MODEL OF COASTAL ZONE HYDROGEOLOGY

The background geomorphological and geological information and results from the field investigations within the coastal zone allow the derivation of a conceptual hydrogeological model for the coastal zone of North Norfolk. The conceptual model is shown in Fig. 15 and was developed from the generic hydrological box model for saltmarsh systems presented by Nuttle *et al.* (1988) and shares some of the features of the schematic model of Howes *et al.* (1996) for Great Sippewisset Marsh, Cape Cod, Massachusetts. The hydrogeological model consists of the following units:

- **Inland recharge area:** This represents the soil zone and unsaturated zone of the inland groundwater catchment area that controls the degree of effective precipitation

that recharges the underlying, saturated Chalk aquifer. This zone includes glacial till, glacial sand and gravel and the soil zone, as well as unsaturated Chalk.

- **Regional Chalk aquifer:** The saturated regional Chalk aquifer underlying the entire area.
- **Coastal zone:** This represents the complex interface between the regional aquifer and surface coastal/marine environment.
- **Sea:** The near-shore, tidal sea to which all hydrological systems ultimately discharge.

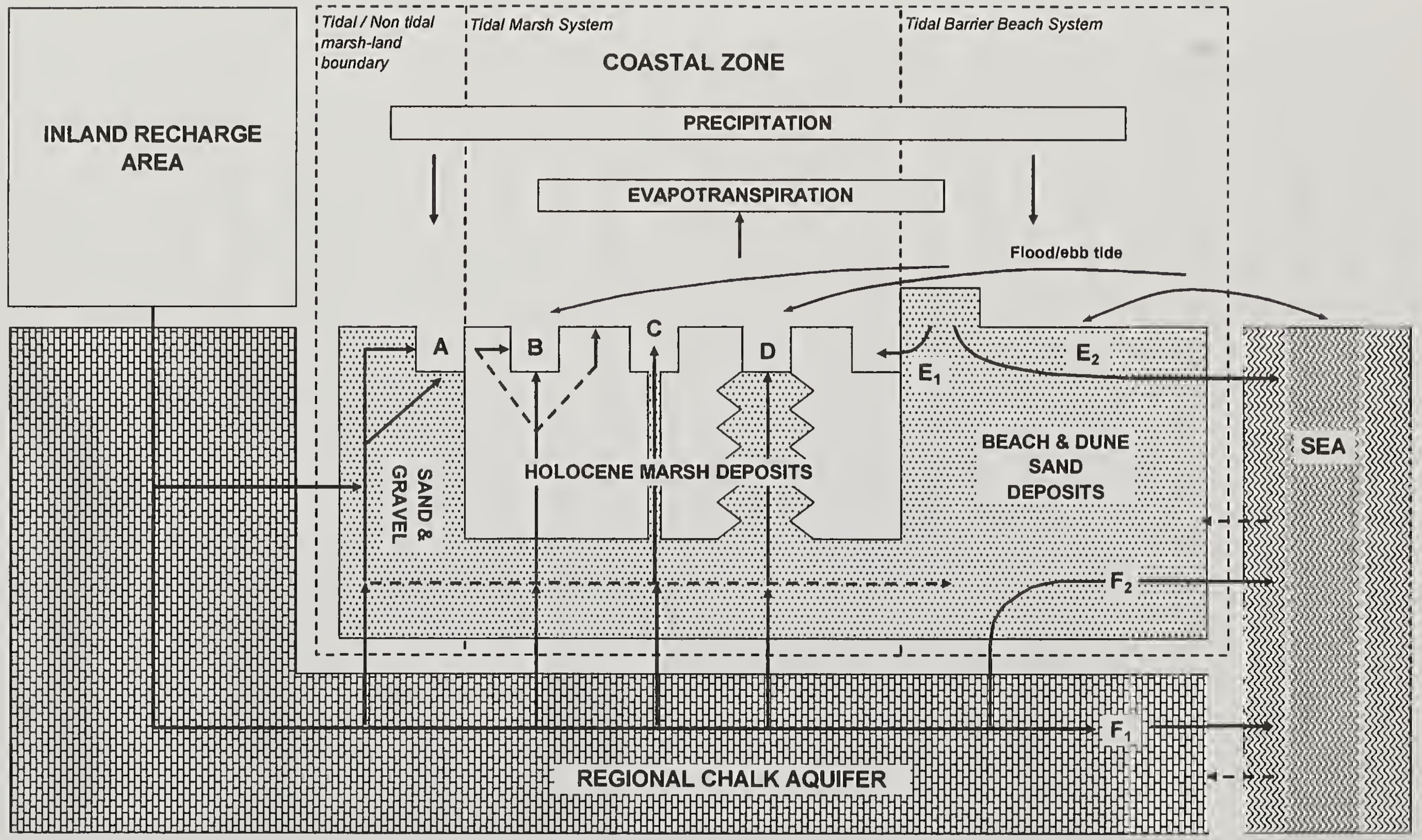
The North Norfolk coastal zone is a complex system consisting of inter-tidal Holocene barrier and back-barrier sediments and pre-Holocene sediments deposited in a structural trough in the underlying Chalk surface. Low-permeability 'back-barrier' marsh sediments form a semi-confining layer to the coastal groundwater system, although various pathways for groundwater transfer to the surface have been identified. No distinction is made between the Holocene barrier sediments (i.e. beach and dune deposits) and the pre-Holocene sand and gravel unit that underlies the marsh, as both these units are composed of granular sand and gravel and are considered hydraulically-equivalent for the purposes of this conceptual model. The geological complexity of the North Norfolk coastal zone suggests that up to six mechanisms of groundwater discharge may facilitate groundwater discharge from the Chalk aquifer and groundwater-surface interaction within the coastal marshes. However, any combination of these mechanisms may occur along specific sections of the coast depending on site-specific factors and the inland catchment characteristics. With reference to Fig. 15, these mechanisms include:

A: Groundwater seepage along land-marsh boundary

Diffuse groundwater discharge, generally from sand and gravel deposits, along the land-marsh boundary. This discharge also includes groundwater from the non-tidal drain network associated with agricultural land that borders the tidal marshes.

B: Groundwater discharge to Holocene marsh deposits

Despite a low hydraulic conductivity, back-barrier marsh deposits can receive a component of groundwater flow by vertical advection from the underlying aquifer. This transfer may result in a net flow of surplus groundwater to the creek system or it may balance evapotranspirative water loss from areas of undrained marsh. This groundwater flux will be



A: Groundwater seepage from a local (pre-Holocene) sand and gravel aquifer.
B: Groundwater discharge to Holocene marsh deposits in reponse to lateral drainage groundwater flow to creeks or evapotranspiration from marsh surface. This mechansim includes both marsh-upland boundary seepage and advection to the internal marsh system (Howes & Weiskel, 1996).
C: Discrete 'spring' discharge direct to tidal creeks.
D: Groundwater seepage to tidal creeks, through permeable channel sand deposits.
E: Seepage from beach sand and dune/barrier system to marsh creeks (E_1) or the sea (E_2).
F: Direct groundwater discharge to the sea from the Chalk aquifer (F_1) or through beach sands (F_2).

- - - ▸ Uncertain groundwater flow path

Fig. 15. Hydrogeological conceptual model for potential mechanisms of groundwater discharge within the coastal system of North Norfolk.

greatest near the landward, feather-edge of the marsh deposits where the hydraulic gradient is greatest and marsh deposits thinnest, and constitutes the land-marsh boundary seepage mechanism described by Howes *et al.* (1996).

C: Discrete spring discharge

Significant spring discharges are a characteristic feature of the North Norfolk coastal zone where they occur in discrete zones within the creek system.

D: Diffuse seepage to creeks through permeable creek bed deposits

The occurrence of channel sands and/or shelly deposits in many tidal creeks may provide a pathway for groundwater exchange within the Holocene back-barrier marsh deposits, depending on the vertical and lateral connectivity with the underlying aquifer.

E: Discharge from the beach and dune/barrier system

The density contrast between seawater and rainwater often results in the formation of a freshwater lens within coarse-grained emergent dune and barrier systems (see Bokuniewicz and Pavlik, 1990). The occurrence of such features within the barrier structures of the North Norfolk coast is supported by the minor abstractions of potable groundwater from coastal dunes (e.g. Holme nature reserve) and by evidence from the electro-magnetic survey of Foley *et al.* (2001) that identified low salinity water within Blakeney Eye. The groundwater contained in a local freshwater lens will be discharged landward to marsh creeks or seaward to the beach face and the sea.

F: Discharge from the Chalk directly to the sea

The semi-confining behaviour of the Holocene marsh deposits may promote the flow of groundwater beneath the marsh system directly to the sea, particularly if rapid-flow pathways exist within the Chalk.

On the basis of the observations within the coastal zone described above and the results of intrusive works undertaken within the coastal zone as part of this study, the conceptual model presented in Fig. 15 can be applied to each of the geological cross-sections presented in Fig. 6. The resulting conceptual hydrogeological cross-sections are presented in Fig. 16 and provide an indication of the hydrogeology in regions of groundwater-active and groundwater-inactive natural salt marsh (Fig. 16a and 16b, respectively), in addition to reclaimed marshes (Fig. 16c).

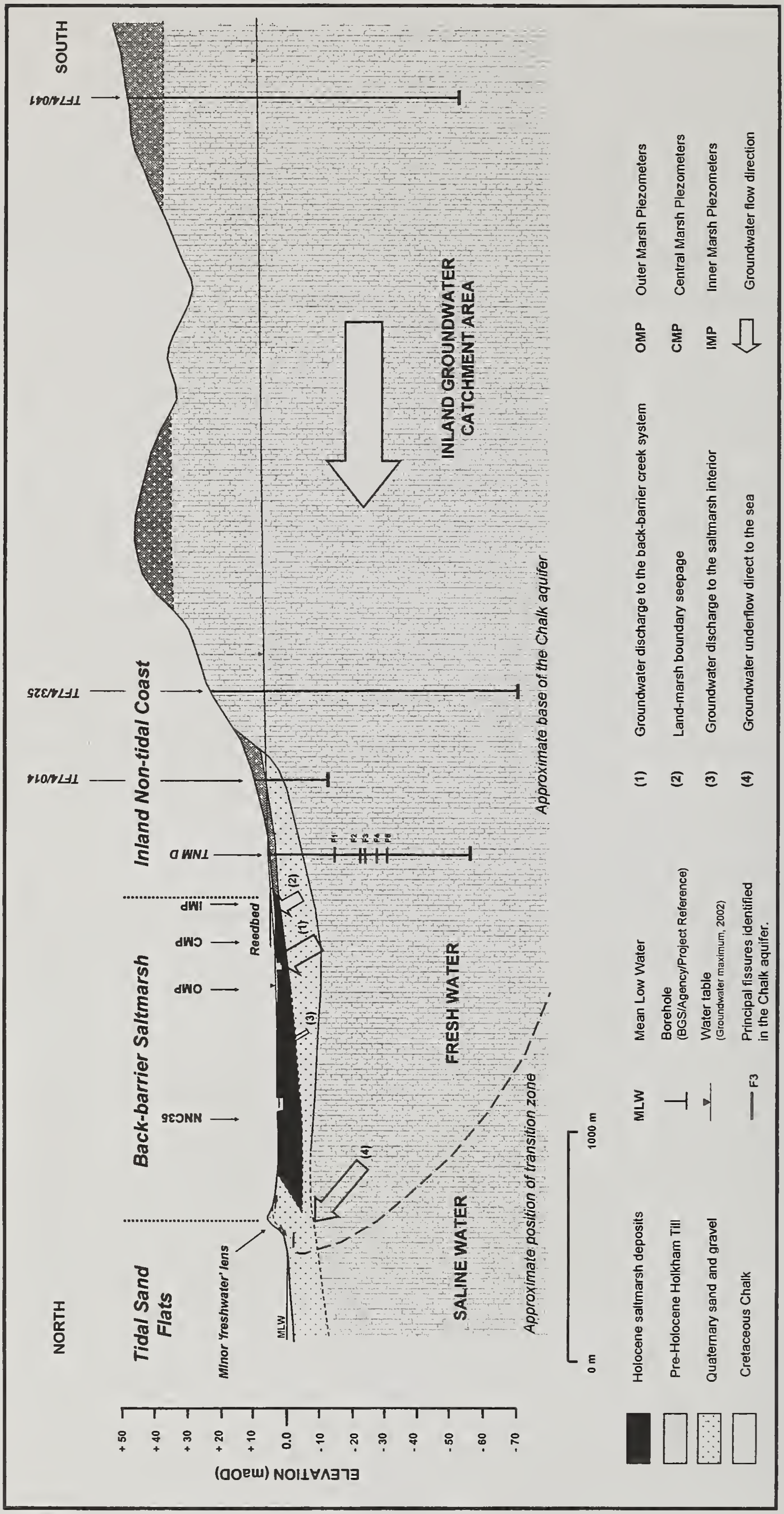


Fig. 16a. Hydrogeological cross-section through groundwater-active coastal marsh (Thornham) within geological unit 1, typical of the western marsh system.

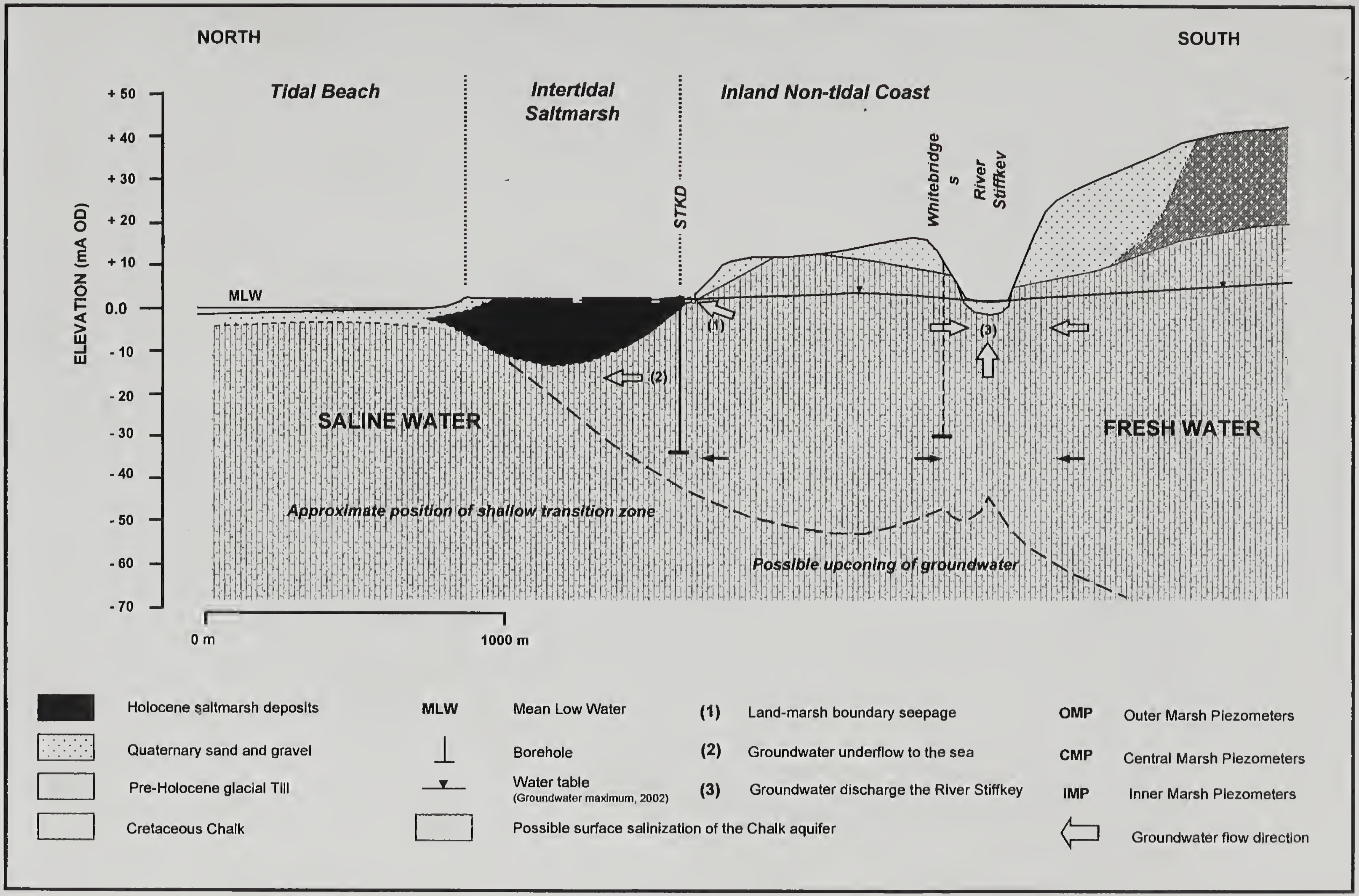


Fig. 16b. Hydrogeological cross-section through groundwater-inactive coastal marsh (Stiffkey) within geological unit 2, typical of the central marsh system.

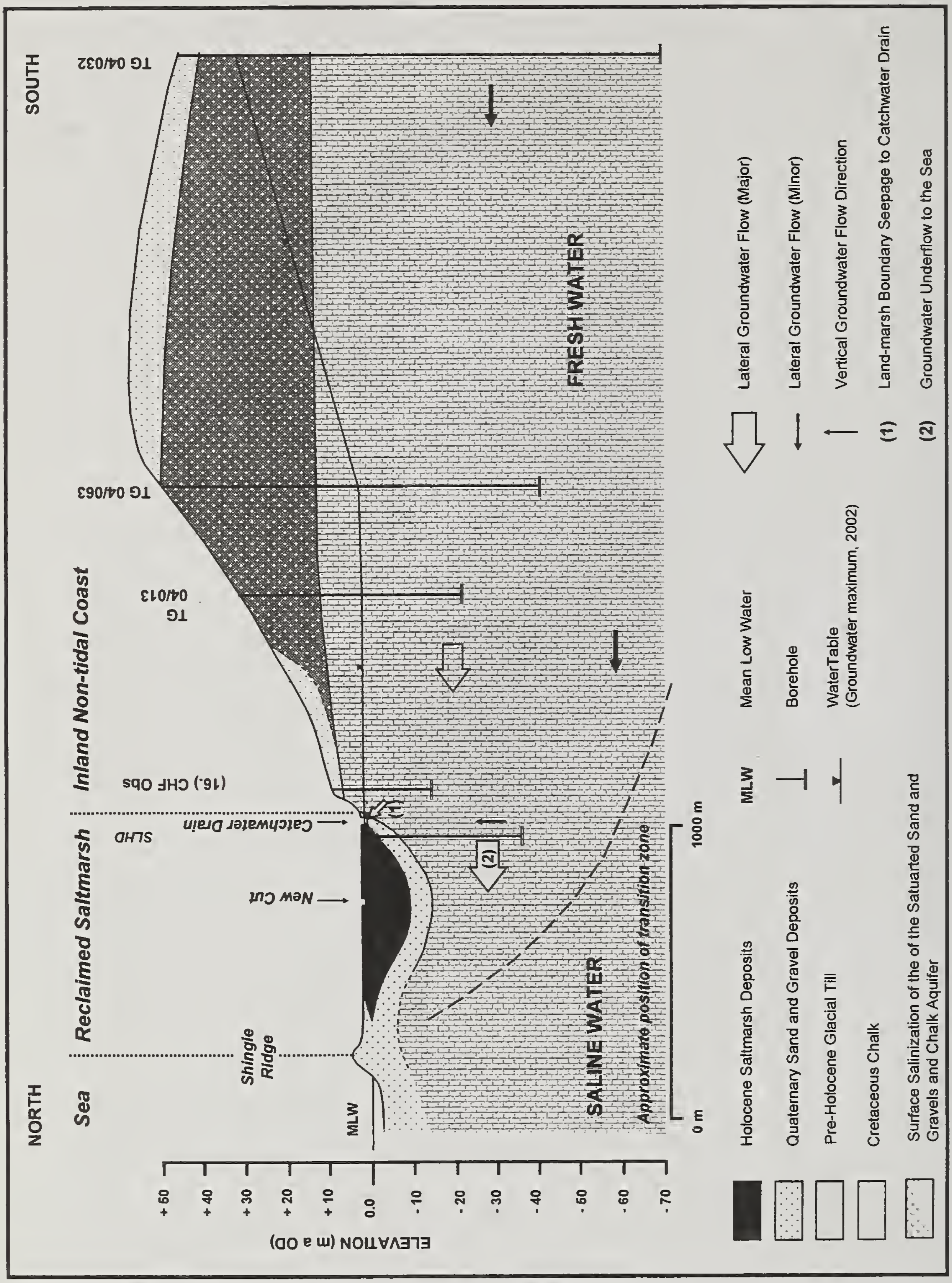


Fig. 16c. Hydrogeological cross-section through reclaimed coastal marsh (Salthouse) within geological unit 3, typical of the eastern marsh system.

CONCLUSIONS

This paper aimed to characterise the hydrogeology of the coastal zone of North Norfolk and to assess the significance of groundwater discharge at the boundary between the inland catchment area and the coastal and marine environment. Six potential mechanisms were identified that represent the complex variation in coastal geomorphology, physiography and geology that control groundwater discharge to the surface within the coastal zone. Any combination of these mechanisms may operate within different sections of the coastal marsh system and each mechanism will have its own significance for the chemistry and nutrient content of discharging groundwater.

Two key zones with characteristic hydrogeology were identified. The coastal saltmarsh west of the River Burn is characterised by a potentially high groundwater influx to the coast, with a geology dominated by comparatively thin Holocene marsh deposits (with a high component of coarser material) that is underlain by significant thicknesses of pre-Holocene sand and gravel overlying the Chalk aquifer. This zone is termed 'groundwater-active saltmarsh' and is characterised by the occurrence of numerous groundwater discharge features that correlate with very low salinities in creeks during ebb-tide drainage. These marshes demonstrate a high degree of groundwater-surface interaction.

In contrast, the saltmarsh between Wells and the mouth of the River Stiffkey has a small groundwater catchment area, with a geology characterised by thick Holocene back-barrier deposits (with little coarse material) and sand and gravel deposits restricted to the centre of the marsh. This zone is termed 'groundwater-inactive saltmarsh' where groundwater discharge is likely to be limited by land-marsh boundary processes.

The remaining coastal sections (reclaimed salt marsh) are dominated by a low to moderate groundwater inflow and the presence of glacial sand and gravel beneath Holocene marsh deposits, which extend up to (and sometimes beyond) the land marsh boundary and whose integrity is thought to be at least partially dependent on a component of freshwater input.

The nature and relative differences in groundwater supply mechanisms to the coastal zone of North Norfolk have significance for the maintenance and restoration of the coastal habitats that depend on freshwater discharges. Successful management of the conservation features of this coastal zone will depend on knowledge of the hydrogeology presented in this paper in the context of groundwater abstractions, and changes in flood defence and water quality as a result of future sea-level rise.

ACKNOWLEDGEMENTS

The authors are grateful to the Natural Environment Research Council and the Environment Agency (Anglian Region) for the award of a CASE studentship to Adrian Green in support of this research. Particular thanks are made to David Burgess, Dave Clarke and Marion Martin of the Environment Agency. The research project was dependent on the successful completion of an intensive programme of fieldwork. This work was only achieved by the support provided by Jenny Stevenson, Charles Anthony Green and Alison Bateman. The success of this research also depended on the co-operation of local landowners, private householders and several organisations. Therefore, particular thanks go to Mr S. Betts of Thornham Farms, Col. T. Blount of Cley Hall Farms, Mr M. Thompson of Thompson Brancaster Farms, Mr N. Deterding of Kelling Hall Farm and Mr A. Borthwick of Deepdale Farm, all of whom allowed Adrian Green access to their land and groundwater observation infrastructure. In addition, thanks go to Mr C. Millar, Mr & Mrs A. Whiteman, Mrs C. Young, Ms R. Edginton and Mr Allison who allowed access to their domestic boreholes throughout the period of the research. The staff at the Titchwell RSPB Bird Reserve and Holme Marshes also provided access to the reserves, groundwater observation infrastructure and areas of non-tidal land on the reserves as required. The authors are also grateful for the technical support provided by staff at the University of East Anglia, in particular Liz Claxton, Laurie Cartwright, Sheila Davies, Paul Disdle and Alan Ovenden.

REFERENCES

ANDREWS, J. E., BOOMER, I., BAILIFF, I. K., BALSON, P., BRISTOW, C., CHROSTON, P. N., FUNNELL, B. M., HARWOOD, G. M., JONES, R. W., MAHER, B. A. & SHIMMIELD, G. 2000. Sedimentary evolution of the north Norfolk barrier coastline in the context of Holocene sea-level change. In: I. Shennan, I & Andrews, J. E. (eds) *Holocene Land-Ocean Interaction and Environmental Change around the North Sea*, Geological Society Special Publication, **166**, 219-251.

ANDREWS, J.E., CORBETT, W.M., FUNNELL, B.M. & BOOTH, S.J. 2002. Pilot study in differentiating North Norfolk glacial sediment using mineral magnetic data. *Bulletin of the Geological Society of Norfolk*, **52**, 73-87.

BOKUNIEWICZ, H., & PAVLIK, B. 1990. Groundwater seepage along a barrier island. *Biogeochemistry*, **10**, 257- 276.

BOOMER, I. 1997. *The Holocene evolution of the North Norfolk coast*. Unpublished Final report, LOIS Special Topic 32. University of East Anglia, Norwich.

CHAPMAN, V.J. 1976. *Coastal Vegetation (2nd ed.)*. Pergamon Press, Oxford.

CHROSTON, P.N., JONES, R. & MAKIN, B. 1999. Geometry of Quaternary sediments along the north Norfolk coast, UK: a shallow seismic study. *Geological Magazine*, **136**, 4, 465-474.

ENTEC UK LIMITED 2003. *Hydro-ecological review of selected European sites: North Norfolk Coast*. Final Report to Environment Agency, 152 pp.

FLOWERS, T.J., HAJIBAGHERI, M.A. & CLIPSON, N.J.W. 1986. Halophytes. *Quarterly Review of Biology*, **61**, 313-337.

FOLEY, A., HULL, W. & CHROSTON, N. 2001. Geophysical demarcation of the saline intrusion at Cley-next-the-Sea, North Norfolk. *Bulletin of the Geological Society of Norfolk*, **51**, 75-104.

FUNNELL, B.M. & PEARSON, I. 1989. Holocene sedimentation on the North Norfolk barrier coast in relation to relative sea-level change. *Journal of Quaternary Science*, **4**, 1, 25-36.

FUNNELL, B.M., 1992. A geological heritage coast: North Norfolk (Hunstanton to Happisburgh). In: Stevens, C., Gordon, J.E., Green, C.P. & Macklin M.G (eds) *Conserving our Landscape: Evolving landforms and ice-age heritage*. English Nature, Peterborough, Crewe, UK, pp. 59-62.

FUNNELL, B.M., BOOMER, I. & JONES, R. 2000. Holocene evolution of the Blakeney Spit area of the North Norfolk coastline. *Proceedings of the Geologists' Association*, **111**, 205-217.

GREEN, A.R. 2004. *The nature and significance of groundwater discharge from the Chalk aquifer to the coastal zone of North Norfolk (UK)*. PhD thesis, University of East Anglia, Norwich.

HOWES, B.L., WEISKEL, P.K., GOEHRINGER, D.D. & TEAL, J.M. 1996. Interception of freshwater and nitrogen transport from uplands to coastal waters: the role of saltmarshes. In: Nordstrum, K.F. & Roman, C.T. (eds) *Estuarine shores: evolution, environment and human alterations*, New York, John Wiley & Sons, pp. 287-310.

NUTTLE, W.K. 1988. The extent of lateral water movement in the sediments of a New England salt marsh. *Water Resources Research*, **24**, 2077-2085.

PACKHAM, J.R. & WILLIS, A.J. 1997. *Ecology of dunes, salt marsh and shingle*. London, Chapman and Hall.

PEARSON, I., FUNNELL, B.M. & McCAVE, I.N. 1990. Sedimentary environments of the sandy barrier/tidal marsh coastline of north Norfolk. *Bulletin of the Geological Society of Norfolk*, **39**, 3-44.

WHEELER, B.D., GOWING, D.J.G., SHAW, S.C., MOUNTFORD, J.O. & MONEY, R.P. 2004. *Ecohydrological guidelines for lowland wetland plant communities* (eds A.W. BROOKS, P.V. JOSE & M.I. WHITEMAN). Environment Agency (Anglian Region), Peterborough, pp. 76-82.

[Manuscript received 28 July 2009; revision accepted 23 December 2009]

APPENDIX 1

Observation Network: Location Maps and Details

Groundwater Active Saltmarsh Study Area (Thornham)

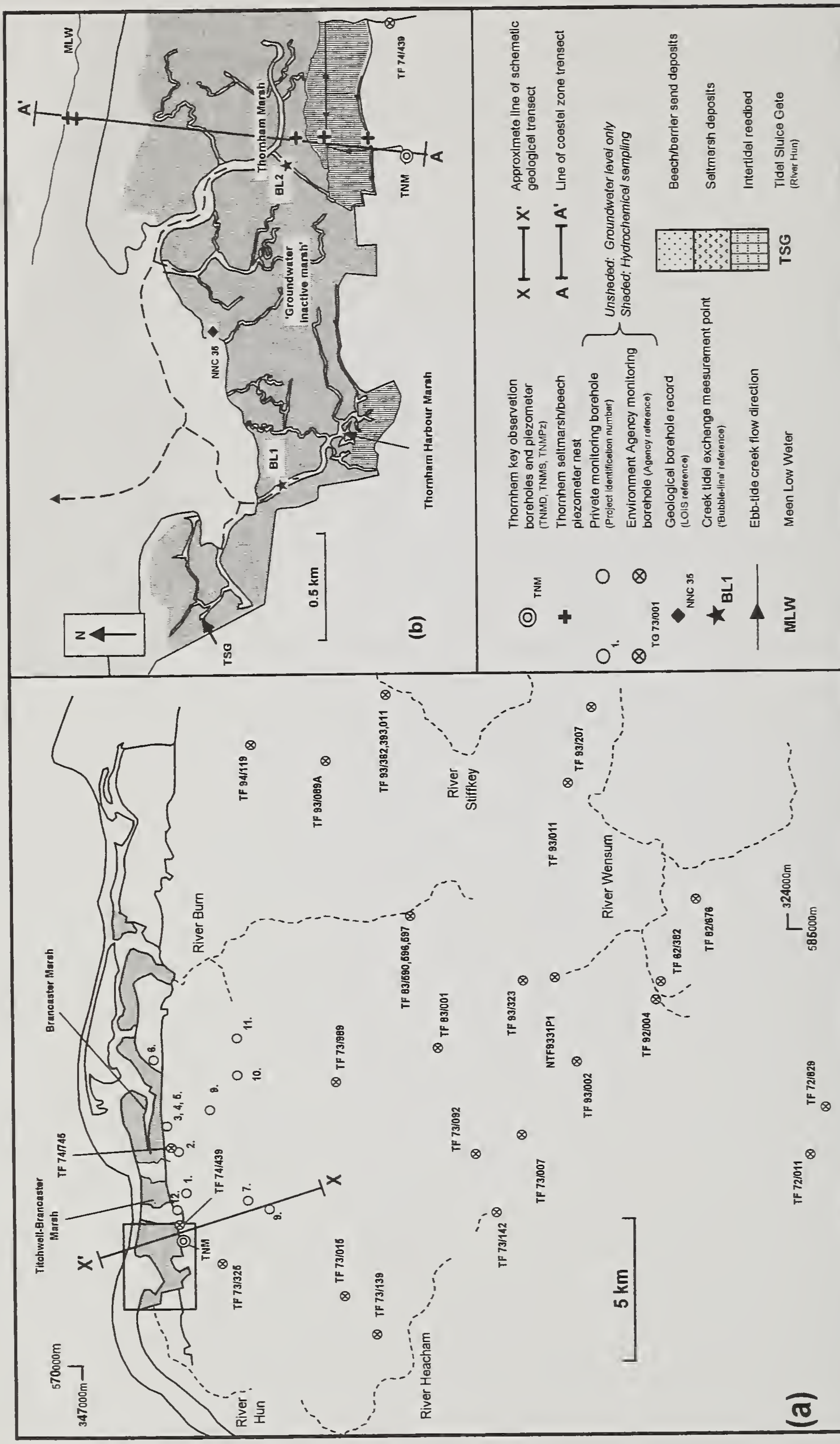


Fig. A1.1 Observation network for the northwest Norfolk groundwater-active saltmarsh study site: (a) Groundwater level observation and sampling network and (b) Detailed groundwater-active saltmarsh study site (Thornham).

Fig. A1.1 Reference	Field Work Reference	Source Name	NGR	Aquifer Unit	Use*
TNM	TNMD	Thornham Deep observation borehole	TF 7437 4368	Chk	Obs.
TNM	TNMS	Thornham Shallow observation borehole	TF 7437 4368	S&G	Obs.
TNM	TNMPz	Thornham Piezometer	TF 7437 4368	S&G	Obs.
1	PF (TWL)	Parker Farms, Titchwell farmyard borehole	TF 7603 4356	Chk	Obs.
2	BRANC PSc	Brancaster Primary School	TF 7748 4381	Chk	Obs.
3	RACKHILL SOUTH	Thompsons of Brancaster Farms, Southern marsh b/h	TF 7835 4419	S&G	Obs.
4	RACKHILL NORTH	Thompsons of Brancaster Farms, Northern marsh b/h	TF 7835 4419	Chk	Obs.
5	RACKHILL PIEZO	Thompsons of Brancaster Farms, marsh piezometer	TF 7835 4419	S&G	Obs.
6	DEEPDALE MARSH	Thompsons, Deepdale marsh spring borehole	TF 8066 4460	?	Obs.
7	PF CHOSELY ROAD OBS	Parker Farms, Chosely road borehole	TF 7576 4158	Chk	Obs.
8	CHOSELY FARMHOUSE	Chosely Farmhouse borehole	TF 7545 4089	Chk	Dom.
9	SUSSEX FARM	Thompsons, Sussex Farm borehole	TF 7891 4279	Chk	Obs.
10	LONG PLANTATION	Thompsons, Long Plantation borehole	TF 8010 4186	Chk	Obs.
11	WESTGATE FARM	Westgate Farm Bungalow	TF 8141 4188	Chk	Dom.
12	TWL RSPB	Titchwell RSPM piezometers	TF 7529 4392	S&G	Obs.
TF74/325	TNM INLAND	Thornham Farms, Lyng Farm, Inland Borehole	TF 7354 4239	Chk	Obs.
TF74/439	TNM RSPB	Thornham Farms, marsh borehole	TF 7490 4380	Chk	Obs.
TF74/745	WHITELADIES	Whiteladies, Brancaster	TF 7757 4405	Chk	Obs.
TF73/988	STATION FARM	Station Farm, Stanhoe	TF 7984 3869	Chk	Obs.
TF73/007	TF73/007	Coe Ltd	TF 77954 32655	-	Obs.
TF73/015	TF73/015	Sedgford PWS	TF 72427 38620	-	Obs.
TF73/092	TF73/092	Bircham Newton	TF 77305 34176	-	Obs.
TF73/136	TF73/136	Sedgeford, Old Station	TF 71011 37408	-	Obs.
TF73/142	TF73/142	Great Bircham, observation borehole	TF 75243 33476	-	Obs.
TF72/011	TF72/011	Old Barn	TF 7714 2333	-	Obs.
TF72/828	TF72/828	Great Massingham	TF 7880 2280	-	Obs.
TF83/001	TF83/001	Barwick Hall, Stanhoe	TF 80996 35344	-	Obs.
TF83/002	TF83/002	Frizzleton Farm	TF 80499 30848	-	Obs.
TF83/323	TF83/323	Syderstone canteen	TF 8330 3256	-	Obs.
TF83/560	TF83/560	South Creake, Chalk observation borehole	TF 8563 3624	-	Obs.
TF83/566	TF83/566	Manor Farm, South Creake	TF 8562 3648	-	Obs.
TF83/567	TF83/567	Old Primary School, S.Creake	TF 8578 3606	-	Obs.
NTF8331P1	NTF8331P1	Syderstone common, P1 Chalk	TF 8344 3153	-	Obs.
TF82/004	TF82/004	The Manor, Rudham	TF 82589 28244	-	Obs.
TF82/005	TF82/005	The village Well, Rougely	TF 83150 20334	-	Obs.
TF82/008	TF82/008	Viper Hall Wood	TF 81509 20769	-	Obs.
TF82/382	TF82/382	Rudham House Farm, East Rudham	TF 8325 2807	-	Obs.
TF82/676	TF82/676	Valley Farm, Helhoughton	TF 8664 2700	-	Obs.
TF94/116	TF94/116	Cuckoo Lodge, Wells-next-the-Sea	TF 9160 4135	-	Obs.
TF93/011	TF93/011	Grove House Farm, Sculthorpe	TF 9015 3103	-	Obs.
TF93/089A	TF93/089A	Egmere P.S. - Bore A	TF 9092 3896	-	Obs.
TF93/207	TF93/207	Fakenham Depot	TF 9271 3031	-	Obs.
TF93/362	TF93/362	The Old Station, Little Walsingham	TF 9322 3687	-	Obs.
TF93/363	TF93/363	Little Walsingham	TF 9160 4135	-	Obs.

***USE: *Obs.* = Observation borehole, *Dom.* = Domestic abstraction borehole, SI = Spray irrigation**

Groundwater-inactive Saltmarsh Study Area (Stiffkey)

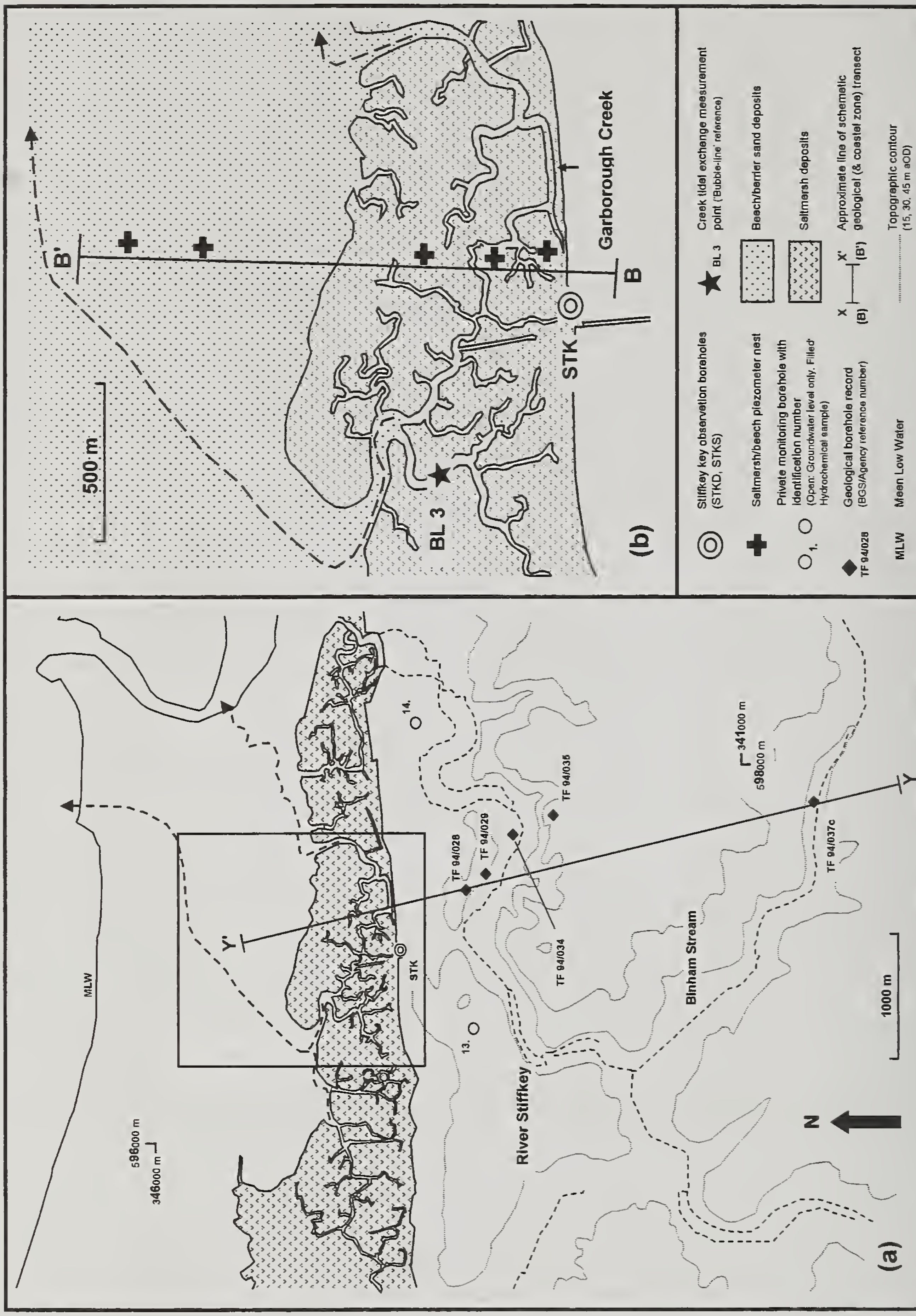


Figure 4.25 Observation network for north Norfolk groundwater-inactive coastal zone study site: (a) Observation network and (b) Detailed groundwater-inactive saltmarsh study site (Stiffkey).

Fig. A1.2 Reference	Field Work Reference	Source Name	NGR	Aquifer Unit	Use*
STK	STKD	Stiffkey Deep Borehole (northern)	TF 9652 4392	Chk	Obs
STK	STKS	Stiffkey Shallow Borehole (southern)	TF 9652 4392	Chk	Obs
13	LONGACRE	Longacre holiday cottage	TF 9589 4329	Chk	Dom
14	WHITEBRIDGES	Whitebridges	TF 9856 4374	Chk	Dom
TF94/116	TF94/116	Cuckoo Lodge, Wells-next-the-sea	TF 9160 4135	-	Obs
TF93/362	TF93/362	The Old Station, Little Walsingham	TF 9322 3687	-	Obs
TF93/089A	TF93/089A	Egmere PWS, observation bh A	TF 9092 3896	-	Obs

***USE: *Obs.* = Observation borehole, *Dom.* = Domestic abstraction borehole, SI = Spray irrigation**

Reclaimed Saltmarsh Study Area (Salthouse)

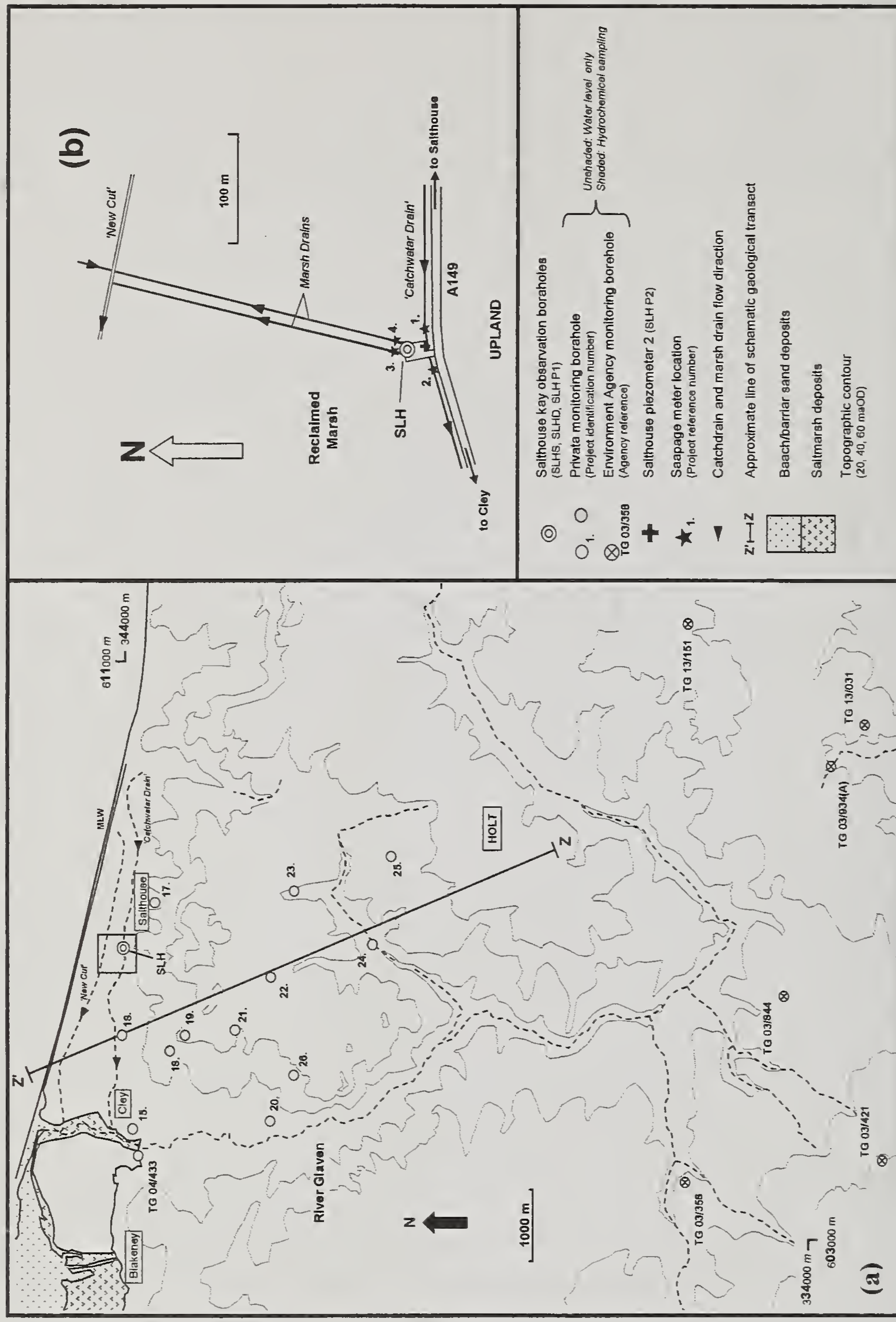


Fig. A1.3 Observation network for north Norfolk reclaimed saltmarsh coastal zone study site: (a) Groundwater level observation network and (b) Detailed reclaimed saltmarsh study site (Salthouse).

Fig. A1.3 Reference	Field Work Reference	Source Name	NGR	Aquifer Unit	Use*
SLH	SLHD	Salthouse Deep Observation Borehole	TG 0704 4400	Chk	Obs.
SLH	SLHS	Salthouse Shallow Observation Borehole	TG 0704 4400	S&G	Obs.
SLH	SLH P1	Salthouse Piezometer 1	TG 0704 4400	Holocene	Obs.
SLH	SLH P2	Salthouse Piezometer 2	TG 0704 4400	S&G	Obs.
15	STONECUTTERS	Stonecutters Cottage, Cley	TG 0458 4390	Chk	Obs.
16	CHF MARSH BH	Cley Hall Farms, Marsh Borehole	TG 0586 4407	Chk	Obs.
17	APPLEWOOD (S'HOUSE) WELL	Applewood, Salthouse	TG 0768 4356	Chk	Obs.
18	CHF BARN	Cley Hall Farms, Barn Borehole	TG 0570 4335	Chk	Obs.
19	CHF SI BOREHOLE	Cley Hall Farms, Spray Irrigation Borehole	TG 0588 4316	Chk	SI
20	AWS GLANFORD OBS	AWS, Glanford PWS, Observation Borehole	TG 0468 4188	Chk	Obs.
21	CHF RECTORTY BH	Cley Hall Farms, Rectory Borehole	TG 0594 4239	Chk	Obs.
22	SWAN LODGE	Swan Lodge	TG 0671 4185	Chk	Dom.
23	KENNELS WELL	The Kennels, Holt Road	TG 0703 4035	n/k	Dom.
24	LOWES FARM	Lowes Farm	TG 0786 4159	Chk	Obs.
25	KELLING RD, S.I.	Deterding, Kelling Road, Spray Irrigation b/h	TG 0831 4008	Chk	SI
26	GLAVEN GRAVEL	Glaven Gravel	TG 0528 4158	Chk	Obs.
TG03/358	-	The Hall, Brinton	TG 0378 3580	-	Obs.
TG03/421	-	Industrial Estate, Melton Constable	TG 0410 3292	-	Obs.
TG03/644	-	Old Lodge BH,Stody	TG 0640 4340	-	Obs.
TG03/934A	-	Street Farm Chk obs, Edgfield	TG 0955 3365	-	Obs.
TG03/934	-	Street Farm Abs BH, Edgefield	TG 0944 3375	-	Obs.
TG04/433	AWS CLEY	Glaven Bridge, Cley	TG 0426 4381	-	Obs.
TG13/031	-	Blackhall Farm, Edgefield	TG 1013 3316	-	Obs.
TG13/151	-	Hole Farm Obs BH, Hempstead	TG 1140 3574	-	Obs.

***USE: *Obs.* = Observation borehole, *Dom.* = Domestic abstraction borehole, SI = Spray irrigation**

APPENDIX 2

Groundwater Observation Network: Borehole Datum Levelling Data

Groundwater-active Saltmarsh Study Site (Thornham)

Borehole Reference	Borehole Name	Datum Elevation (m aOD)	Source of Datum Elevation*
INNER MARSH PIEZOMETERS - P1 South	-	5.05	ARG
INNER MARSH PIEZOMETERS - P2 North	-	5.49	ARG
INNER MARSH PIEZOMETERS - P3 Middle	-	5.25	ARG
Marsh Level at I/M.B.P.	-	3.94	ARG
Base of creek south of piezometers	-	3.28	ARG
Base of N-S Creek running from TNM boreholes	-	3.36	ARG
CENTRAL MARSH PIEZOMETERS - P1 North	-	4.83	ARG
CENTRAL MARSH PIEZOMETERS - P2 Middle/North	-	4.23	ARG
CENTRAL MARSH PIEZOMETERS - P3 Middle/South	-	4.38	ARG
CENTRAL MARSH PIEZOMETERS - P4 South	-	4.85	ARG
Marsh Level at Central Marsh Piezometers	-	3.30	ARG
Base of creek to south of C.M.P.	-	1.79	ARG
OUTER MARSH PIEZOMETERS - P1 West	-	4.49	ARG
OUTER MARSH PIEZOMETERS - P2 Middle/West	-	3.72	ARG
OUTER MARSH PIEZOMETERS - P3 Middle/East	-	4.28	ARG
OUTER MARSH PIEZOMETERS - P4 East	-	4.12	ARG
Marsh level at O.M.P	-	3.15	ARG
Base of main creek north of O.M.P.	-	0.93	ARG
Freshwater Poor Creek South of OMP	-	1.55	ARG
Freshwater Rich Creek - Site of BL2 (Fig 4.1b)	-	1.04	ARG
SOUTHERN BEACH PIEZOMETERS - P1 West	-	-0.20	ARG
SOUTHERN BEACH PIEZOMETERS - P2 Middle	-	0.27	ARG
SOUTHERN BEACH PIEZOMETERS - P3 East	-	-0.22	ARG
Beach level at southern/landward piezometers	-	-0.37	ARG
NORTHERN BEACH PIEZOMETERS - P1 West	-	-0.96	ARG
NORTHERN BEACH PIEZOMETERS - P2 Middle	-	-0.98	ARG
NORTHERN BEACH PIEZOMETERS - P3 East	-	-1.02	ARG
Beach level at nothern/seaward piezometers	-	-1.22	ARG
TNMD	Thornham Deep observation borehole	6.28	ARG
TNMS	Thornham Shallow observation borehole	5.98	ARG
TNMPz	Thornham Piezometer	6.56	ARG
TNM RSPB	Thornham Farms, marsh borehole	6.14	ARG
PF (TWL)	Parker Farms, Titchwell farmyard borehole	15.99	ARG
BRANC PSc	Brancaster Primary School	12.62	ARG
WHITELADIES	Whiteladies, Brancaster Staithe	11.26	EA
RACKHILL SOUTH	Thompsons of Brancaster Farms, Southern marsh borehole	6.66	ARG
RACKHILL NORTH	Thompsons of Brancaster Farms, Northern marsh borehole	6.74	ARG
RACKHILL PIEZO	Thompsons of Brancaster Farms, marsh piezometer	6.90	ARG
DEEPDALE MARSH	Thompsons, Deepdale marsh spring borehole	3.69	ARG
THORNHAM INLAND	Thornham Farms, Lyng Farm, Inland Borehole	27.25	ARG
CHOSELY FARMHOUSE	Chosely Farmhouse borehole	48.07	ARG
PF CHOSELY ROAD OBS	Parker Farms, Chosely road borehole	34.10	ARG
LONG PLANTATION	Thompsons, Long Plantation borehole	36.41	ARG
SUSSEX FARM	Thompsons, Sussex Farm borehole	34.68	ARG
AWS SEDGEFORD OBS	Sedgford PWS		EA
STATION FARM	Station Farm, Stanhoe	45.45	EA
WESTGATE FARM	Westgate Farm Bungalow	43.13	ARG

* ARG denotes levelling undertaken by A.R. Green, EA denotes Environment Agency datum

Groundwater-inactive Saltmarsh Study Site (Stiffkey)

Borehole Reference	Borehole Name	Datum Elevation (m aOD)	Source of Datum Elevation*
STKD (Northern/Seaward)	Stiffkey Deep Borehole	4.38	ARG
STKS (Southern/Campsite)	Stiffkey Shallow Borehole	4.39	ARG
INNER MARSH PIEZOMETERS - P1 South	-	3.93	ARG
INNER MARSH PIEZOMETERS - P2 Middle	-	3.71	ARG
INNER MARSH PIEZOMETERS - P3 North	-	3.62	ARG
Marsh Elevation at I.M.P	-	2.77	ARG
Elevation of Caraborough creek (with springs)	-	1.35	ARG
Elevation of main creek b/w C.M.P and O.M.P	-	1.07	ARG
CENTRAL MARSH PIEZOMETERS - P1 South	-	4.25	ARG
CENTRAL MARSH PIEZOMETERS - P2 Middle	-	3.68	ARG
CENTRAL MARSH PIEZOMETERS - P3 North	-	3.89	ARG
Marsh Elevation at C.M.P.	-	2.79	ARG
OUTER MARSH PIEZOMETERS - P1 West	-	3.93	ARG
OUTER MARSH PIEZOMETERS - P2 Middle	-	3.63	ARG
OUTER MARSH PIEZOMETERS - P3 East	-	3.77	ARG
Marsh Elevation at O.M.P.	-	2.72	
SOUTHERN BEACH PIEZOMETERS - P1 South	-	2.09	ARG
SOUTHERN BEACH PIEZOMETERS - P2 Middle	-	2.03	ARG
SOUTHERN BEACH PIEZOMETERS - P3 North	-	1.95	ARG
Beach Elevation at S. B.P.	-	1.73	ARG
NORTHERN BEACH PIEZOMETERS - P1 Middle	-	1.80	ARG
NORTHERN BEACH PIEZOMETERS - P2 South	-	1.93	ARG
NORTHERN BEACH PIEZOMETERS - P3 North	-	1.31	ARG
Beach Elevation at Northern N.B.P.	-	1.25	ARG
LONGACRE COTTAGE, STK	Longacre, Stiffkey	16.97	ARG
WHITEBRIDGES	Whitebridges, Stiffkey	7.88	ARG

*** ARG denotes levelling undertaken by A.R. Green**

Reclaimed Saltmarsh Study Site (Salthouse)

Borehole Reference	Borehole Name	Datum Elevation (m aOD)	Source of Datum Elevation*
SLHD (Northern/Seaward)	Salthouse Deep Observation Borehole	2.63	ARG
SLHS (Southern/landward)	Salthouse Shallow Observation Borehole	2.66	ARG
SLH P1	Salthouse Piezometer 1	3.18	ARG
SLH P2	Salthouse Piezometer 2	3.10	ARG
CATCHDRAIN DATUM	-	4.45	ARG
CATCHDRAIN BOTTOM	-	1.63	ARG
WEST MARSH DRAIN BOTTOM (Seepage Meter)	-	1.38	ARG
s/w level in west drain	-	*1.59*	ARG
EAST MARSH DRAIN BOTTOM (Seepage Meter)	-	1.03	ARG
s/w level in east drain	-	*1.53*	ARG
APPLEWOOD (SALTHOUSE) WELL	Applewood, Salthouse	14.91	ARG
AWS GLANFORD OBS	AWS, Glanford PWS, Observation Borehole	4.78	HSI
AWS CLEY OBS	AWS, Glaven Bridge Observation Borehole, Cley	3.61	HSI
LOWES FARM	Lowes Farm	41.74	HSI
KELLING RD, S.I.	Deterding, Kelling Road, Spray Irrigation Borehole	58.56	ARG
KENNELS WELL	The Kennels, Holt Road	21.03	ARG
CHF MARSH BH	Cley Hall Farms, Marsh Borehole	7.73	Outer
		7.53	Inner
CHF SI BOREHOLE	Cley Hall Farms, Spray Irrigation Borehole	47.81	HSI
CHF RECTORTY BH	Cley Hall Farms, Rectory Borehole	46.62	HSI
CHF BARN	Cley Hall Farms, Barn Borehole	32.10	HSI
SWAN LODGE	Swan Lodge, Holt Road	46.56	ARG
GLAVEN GRAVEL	Glaven Gravel	28.40	ARG
STONECUTTERS	Stonecutters Cottage, Cley	7.66	ARG

*** ARG denotes levelling undertaken by A.R. Green, EA denotes Environment Agency datum, HSI denotes Hydrogeological Services Datum**

APPENDIX 3

Observation Boreholes: Geological and Borehole Construction Details

Groundwater-active Saltmarsh Study Site (Thornham) (NG RTF 7437 4368)

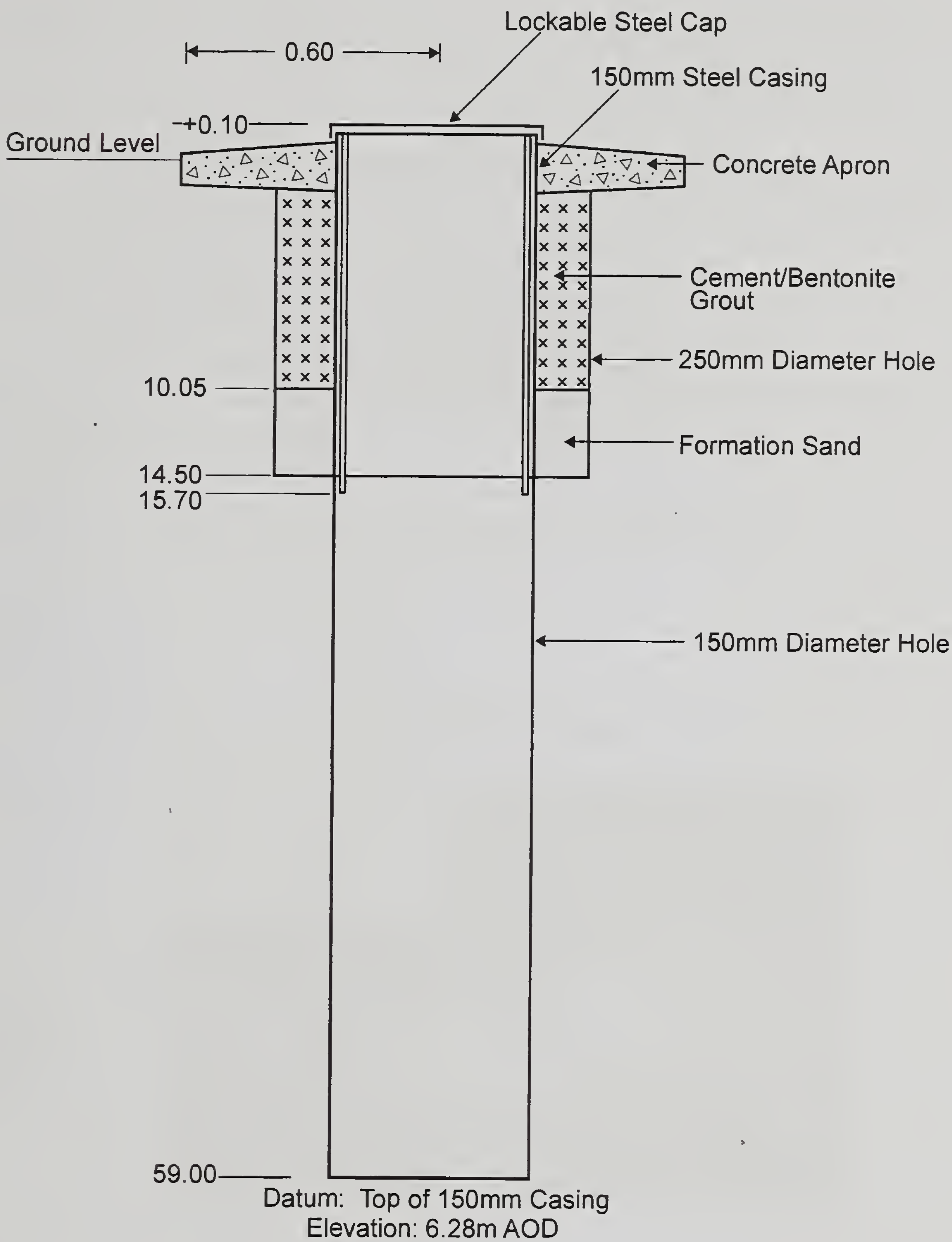
Geological Log (Surface Deposits 0 – 9.5m)

(Depth)	Ground Surface	(Hydrogeological Classification)
0.0 m		
	Dark, clay-rich chalky Soil (clast rich, incl flint & Chalk)	-
0.75 m		
1.0	**Red/brown Sandy Clay** (*Hunstanton Till*) (or sand with clay, or a clayey sand? clast rich, some Chalk)	**AQT**
1.5 m		
2.0		
	Chalk free, orange/brown Silty Sand (large component of a fine sand 'matrix')	**POOR AQF**
3.0	(increasing silt component and decreasing sand grain size with depth) Fining down Series	
4.0	*(?Gradual transition or discrete units? – Posiblys discrete considering the chalk clasts)*	
4.25 m		
5.0		
	Light brown, *Chalk* rich, Sand (Fine sand 'matrix', with significantly less 'silt' than above) Sand becoming finer down section	**AQF**
6.0	Becoming lighter in colour (?more chalky?) down section Flint and Chalk dominant clasts	
7.0		
8.0		
8.75 m		
9.0	**Chalk rich, Sandy Gravel** (with some fine sand. Chalk clasts highly reworked and all sizes)	**AQF**
9.5 m		
	Hard CHALK	**AQF**

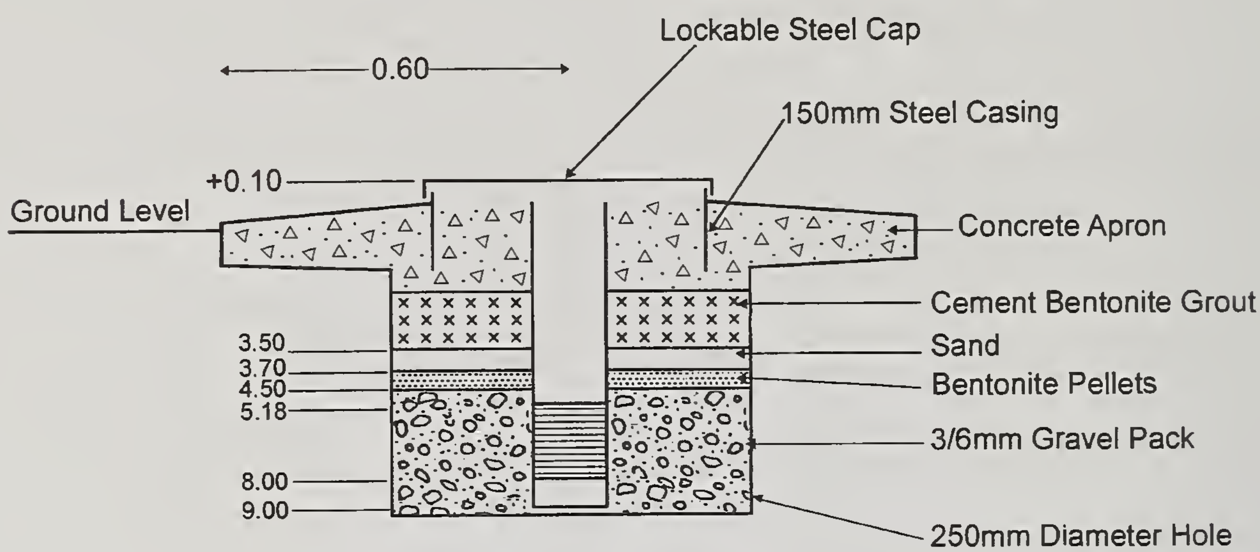
Complete Geological Log (0 – 59 m)

	Ground Surface		
0.0 m			
0.75 m		Soil	
		Holkham Till	
?4.0m?	**Glacial 'Drift' Deposits**		
		Chalk Rich Fine Sands	
8.75 m			
		Basal Sandy Gravel	
9.5 m			
10			
	Flint Poor Hard Chalk	*Flint Poor Chalk*	
15			
19.0 m			*Marl/Clay Free Chalk*
20			
	Flinty Hard Chalk	*Flinty Chalk (light/pale grey flint)*	
25.0 m			
			'clots of grey putty-like grey material (i.e. marl/clay)
30			
31.5 m			
35	**Flint Poor Hard Chalk with Marl Bands**	*Flint Poor Chalk (pale grey flint)*	*Pieces of Marl/ Clay Lamina with the Chalk fragments*
40			
45			
50			
55			
59.0 m			
	BASE OF BOREHOLE		

CONSTRUCTION - Thornham Deep Borehole (TNMD)

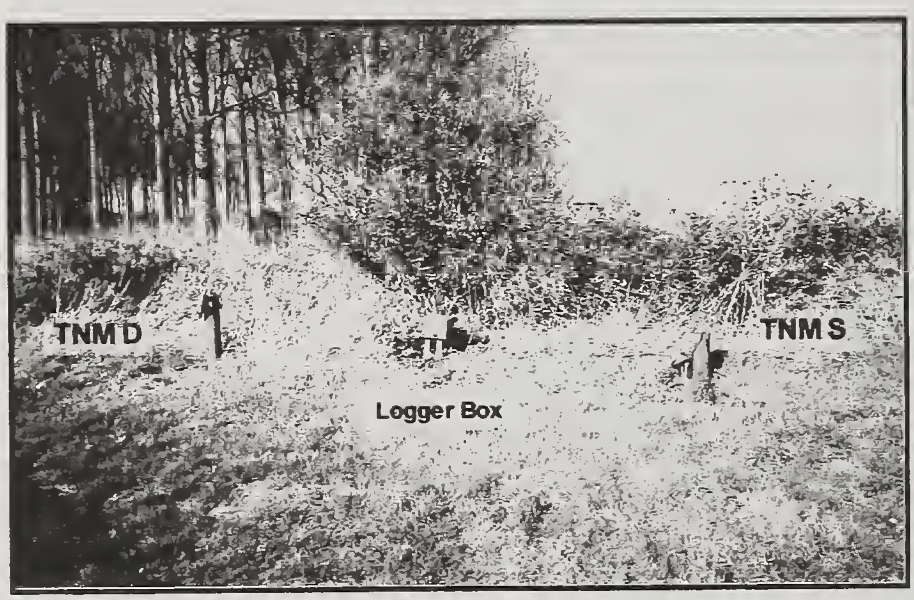


CONSTRUCTION - Thornham Shallow Borehole (TNMS)



Datum: Top of 90mm Casing
Elevation: 5.98m AOD

SITE LAYOUT



Groundwater-inactive Saltmarsh Study Site (Stiffkey) (NG RTF 9652 4392)

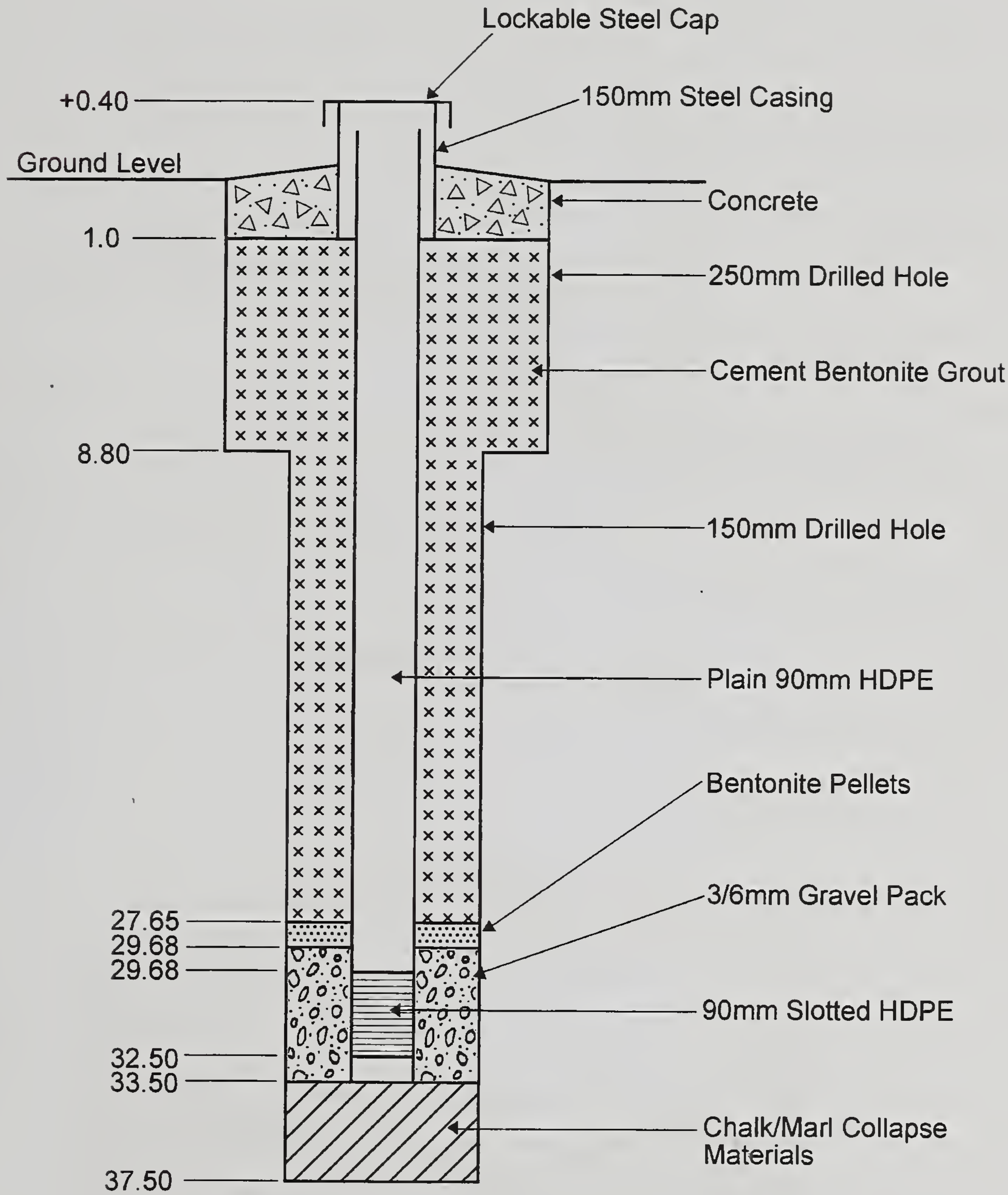
Geological Log (Surface Deposits 0 – 5 m)

(Depth)	Ground Surface	(Hydrogeological Classification)
0.0 m	--	
	Dark brown, Chalky Loam Soil	
-		
1.0		
1.25 m	--	
	Brown, fine-sand/silty Clay *(Holocene Deposits)*	**AQT**
2.0	Contains numerous clasts predominantly angular flint, some chalk	
2.5 m	--	
3.0	**Stiff, dark brown Clay** *(Holocene saltmarsh deposits)*	
	(contains shell fragments and minor clasts)	**AQC/AQT**
3.5 m	--	
4.0		
	Pale, chalky-brown, Chalk rich Clay *(?Holocene deposit?)*	**AQT**
5.0 m	--	
	Hard CHALK	**AQF**

Complete Geological Log (0 – 38 m)

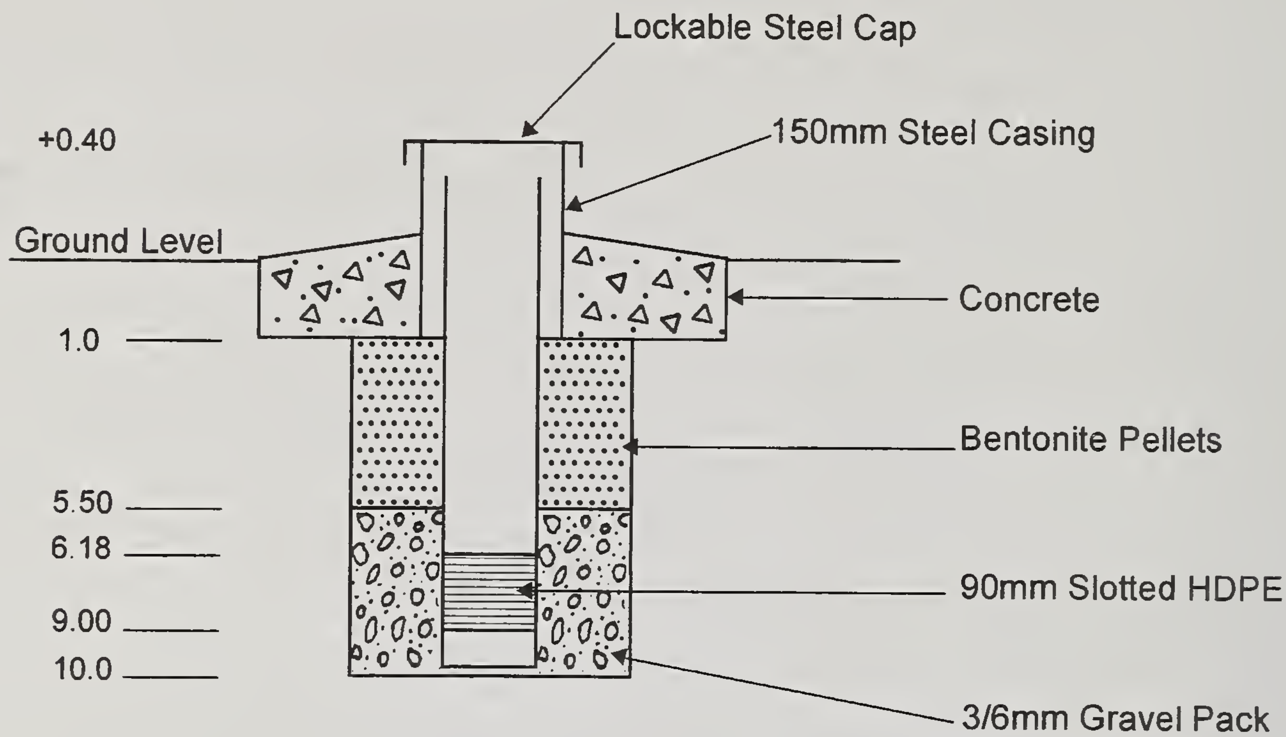
	Ground Surface	
0.0 m	----------	----------
1.25 m		Soil
2.5 m	**Holocene**	Brown, fine sand/silty Clay
3.5 m	**saltmarsh deposits**	Stiff Clay
		Pale, Chalk rich Clay
5.0 m	----------	----------
	Soft & brittle, flinty Chalk	
7.0 m	----------	
		White colour
9.0 m	**Soft & brittle, flinty Chalk** (dark flints)	----------
12.0 m	----------	
15		Yellow colour (apparently resulting from yellow laminations in the Chalk)
20		----------
	(extremely ‘re-worked’) Soft & brittle, flint poor Chalk	
25.0		Becoming whiter
30		
35		
38.0 m	----------	----------
	BASE OF BOREHOLE	

CONSTRUCTION - Stiffkey Deep Borehole (STK D)



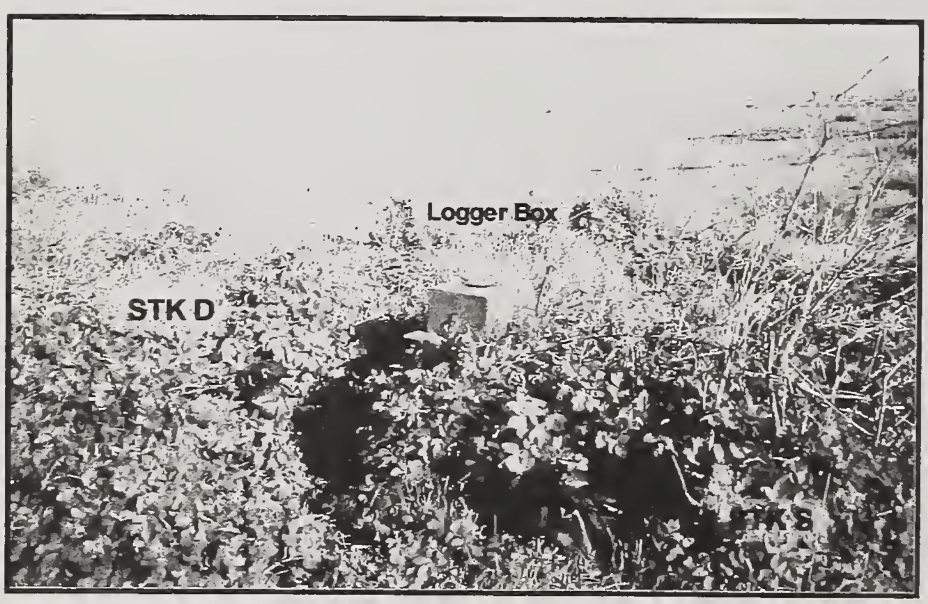
Datum: Top of 90mm Casing
Elevation: 4.38m AOD

CONSTRUCTION - Stiffkey Shallow Borehole (STK S)



Datum: Top of 90mm Casing
Elevation 4.39m AOD

SITE LAYOUT



Reclaimed Saltmarsh Study Site (Salthouse) (NGR TG 0704 4400)

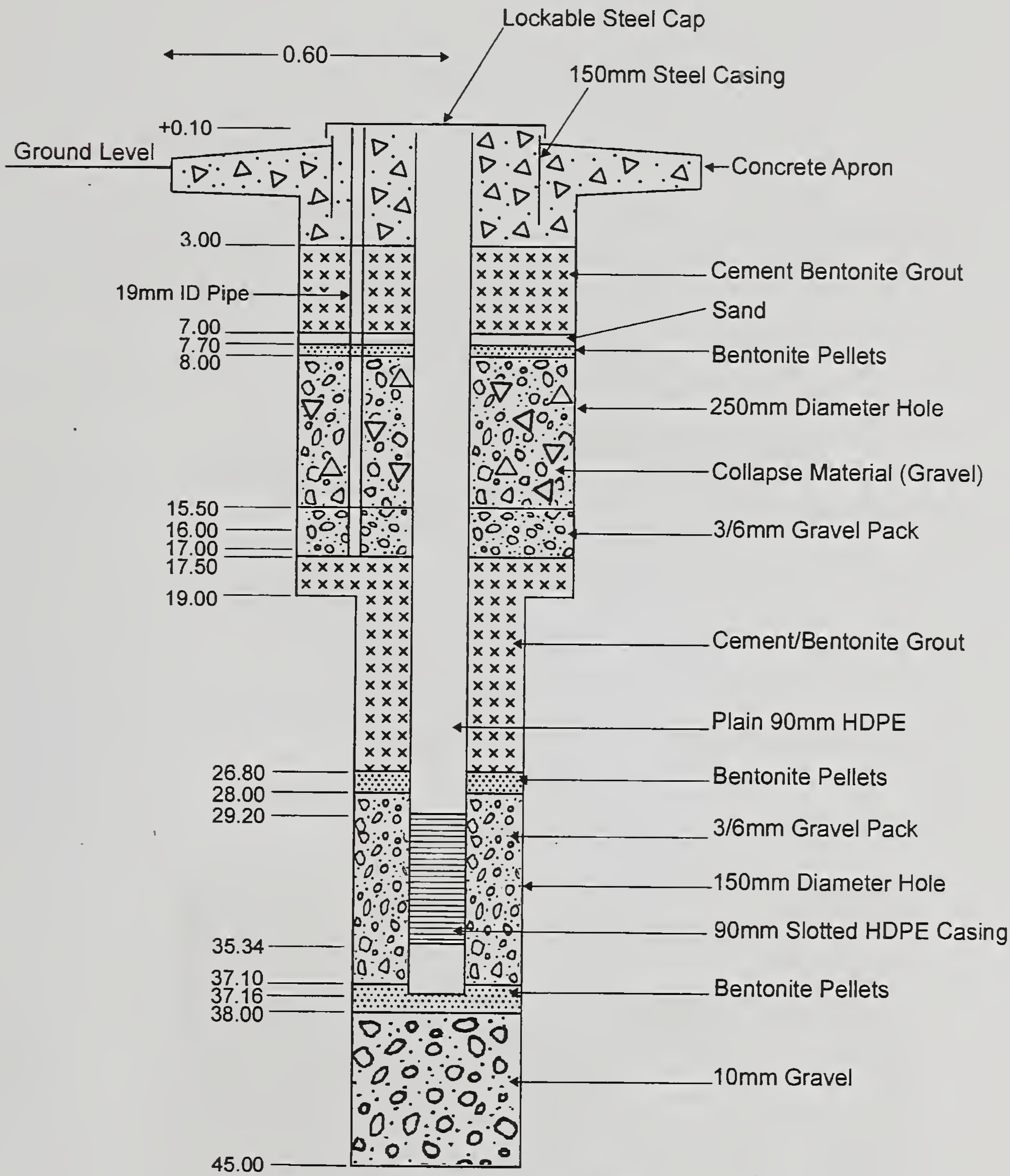
Geological Log (Surface Deposits 0 – 9.5 m)

(Depth)	Ground Surface	(Hydrogeological Classification)
0.0 m	--	
	Clay rich soil -----?--?----	
1.0		
2.0	**Stiffy brown clay** (>50% clay, some small chalk fragments and some other clasts) *(?transition rather than discrete units?)*	**AQC/AQT**
2.5 m	--	
3.0	**Black Sandy Clay** (with shell fragments, little Chalk – *Holocene saltmarsh muds?*)	**AQT**
3.4 m	--	
4.0	**Chalk free, poorly sorted, Sand and Gravel** *(?Gradual transition to clayey sand, rather than discrete units?)*	**AQF**
4.2 m	?----------------?----------------?--------	
5.0	**Chalk free Sandy Clay**	**AQT**
5.2 m	--	
6.0		
7.0	**Poorly sorted, chalk rich, Sand and Gravel** (increasing chalk component with depth) Contains very large cobbles (>15 cm)	**AQF**
8.0		
9.0		
9.5 m	--	
	Hard CHALK	**AQF**

Complete Geological Log (0 – 38.0 m)

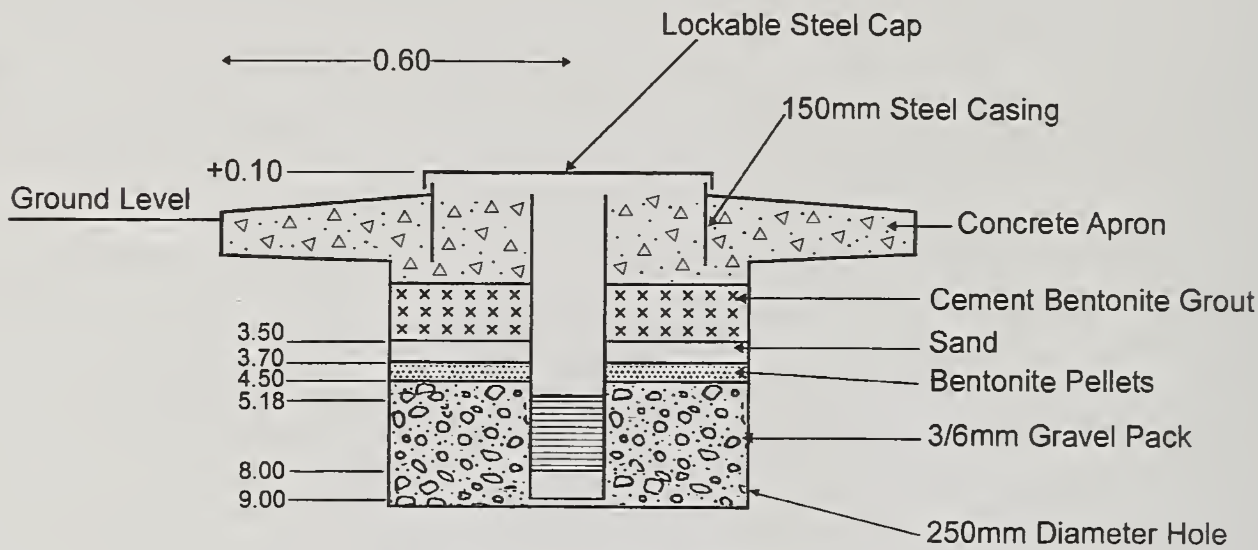
0.0 m	--	--
1.0 m		Soil
2.5 m	**Holocene Deposits**	Stiff Brown Clay
		Black Sandy Clay
3.4 m	--	--
4.2 m		Chalk free/poor Sand and Gravel
5.2 m		Chalk free/poor Sandy Clay
	Glacial 'Drift' Deposits	
		Chalk rich Sand and Gravel
9.5 m	--	--
10		
	Strongly 're-worked' soft & brittle Chalk	
14.5	--	
15		
	'Re-worked' soft & brittle, flinty, Chalk	
20		
24.5	--	
25		
30	**Strongly 're-worked' soft & brittle Chalk**	
35		
38.0 m	--	
	BASE OF BOREHOLE	

CONSTRUCTION - Salthouse Deep Borehole (SLH D)



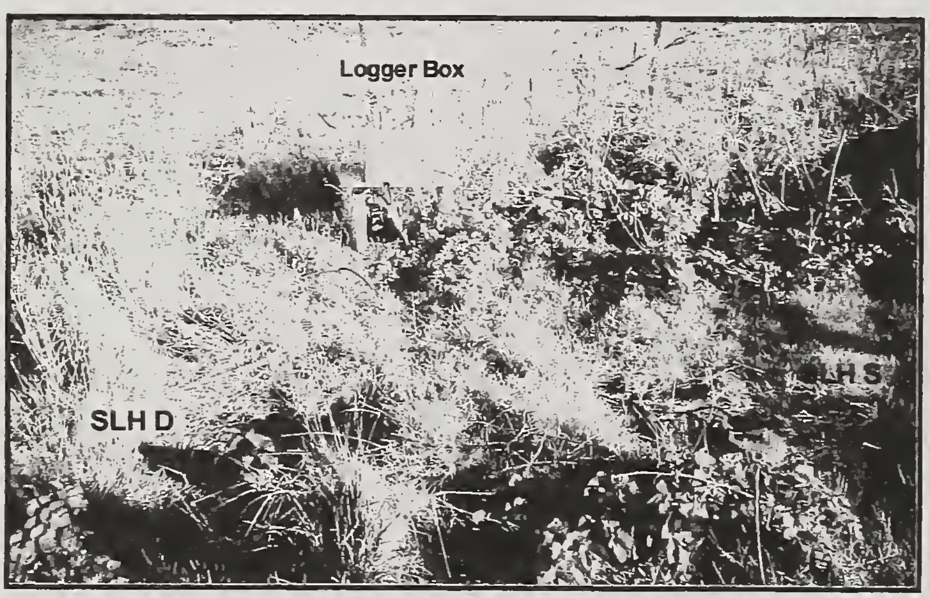
Datum: Top of 90mm Casing
Elevation: 2.63m AOD

CONSTRUCTION - Salthouse Shallow Borehole (SLH S)



Datum: Top of 90mm Casing
Elevation: 2.66 m AOD

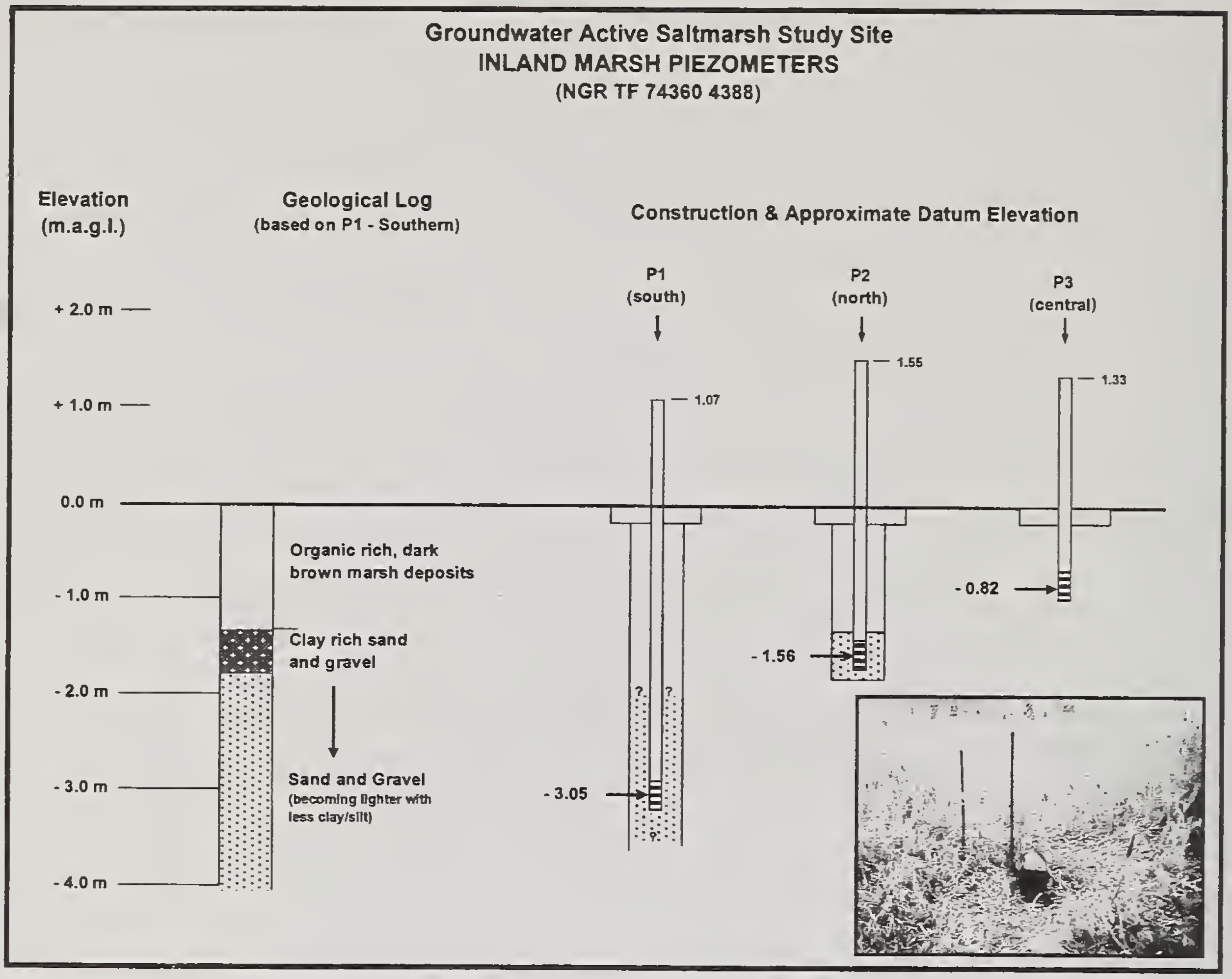
SITE LAYOUT

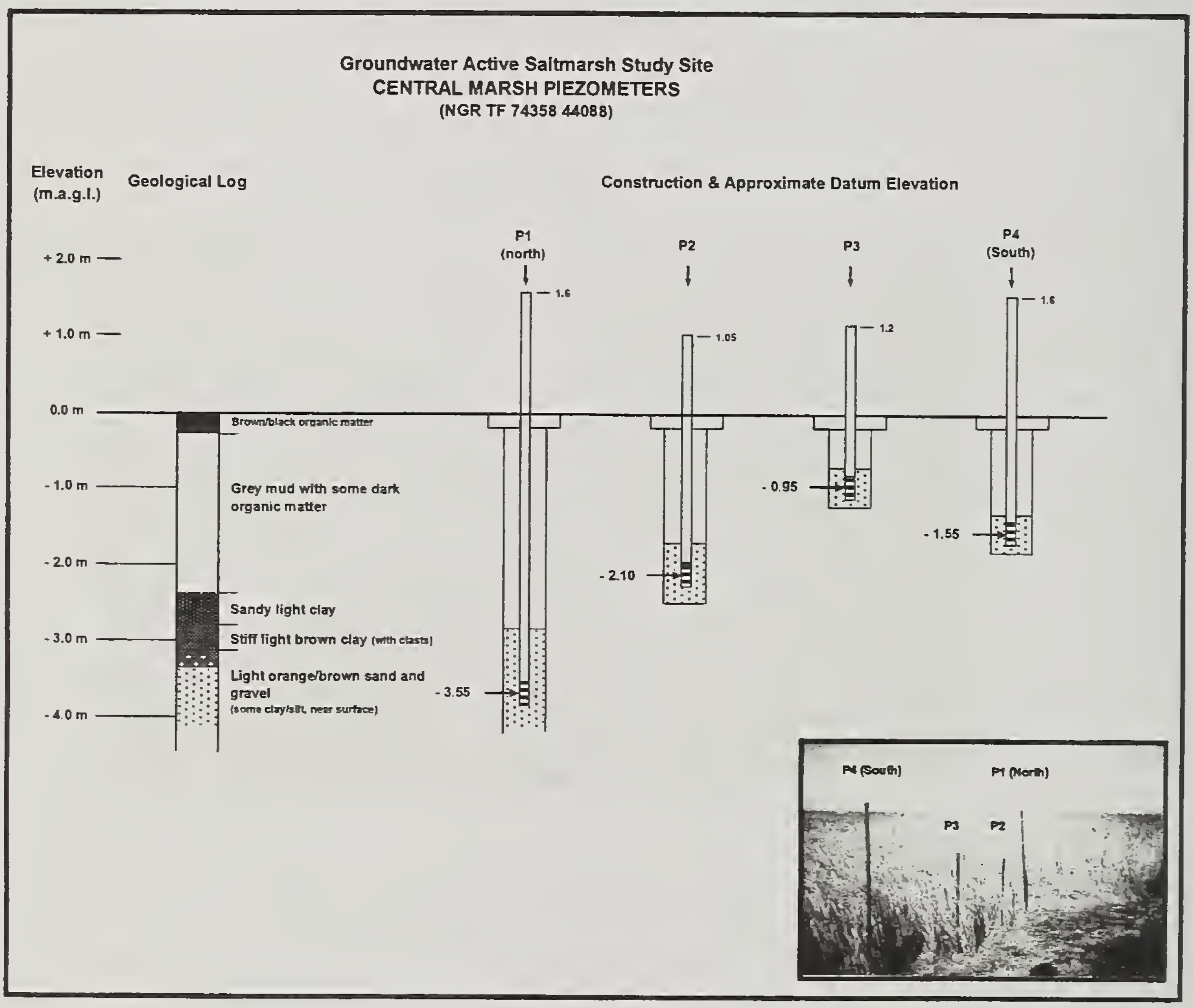


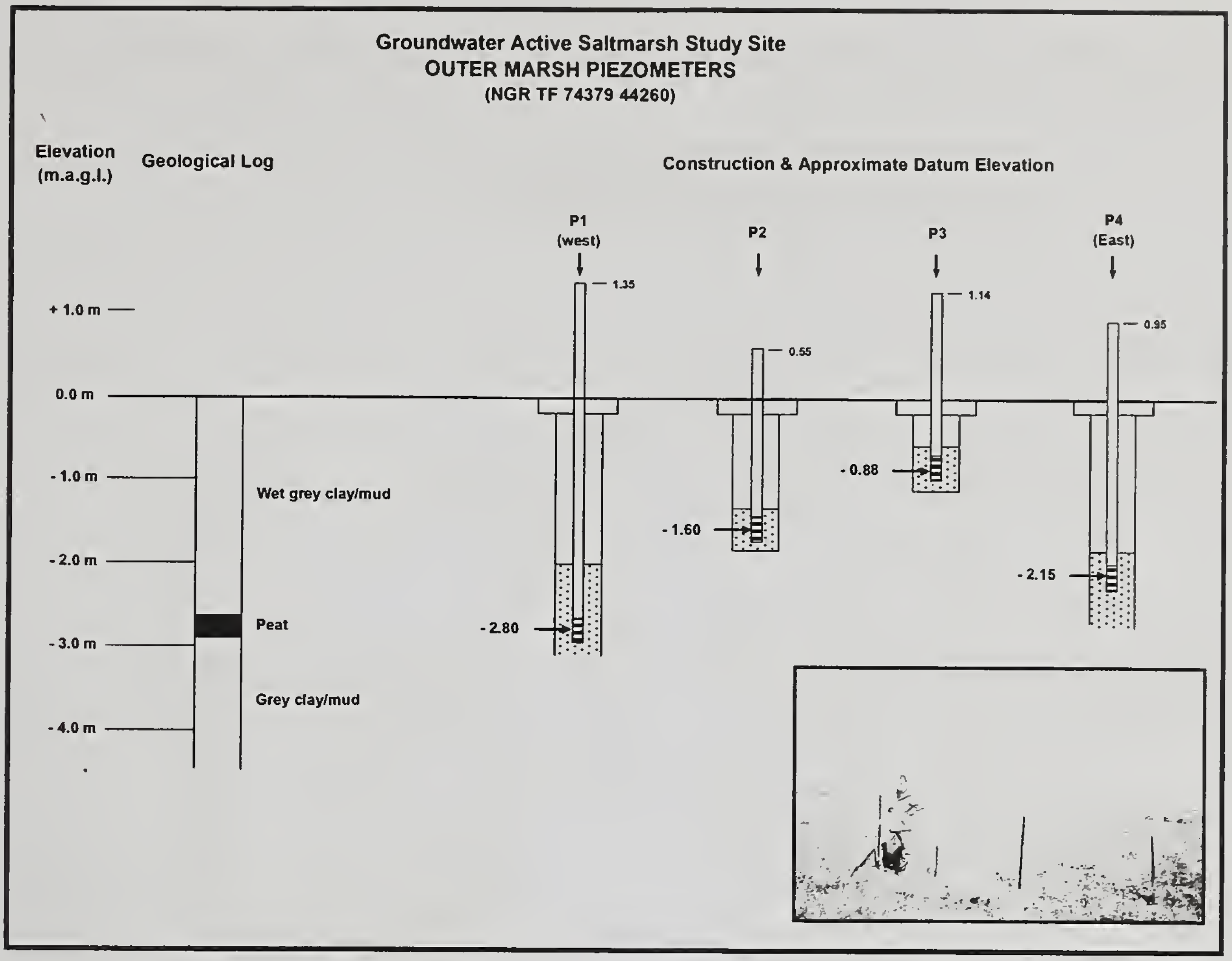
APPENDIX 4

Marsh and Beach Piezometer Transects: Geological and Construction Details

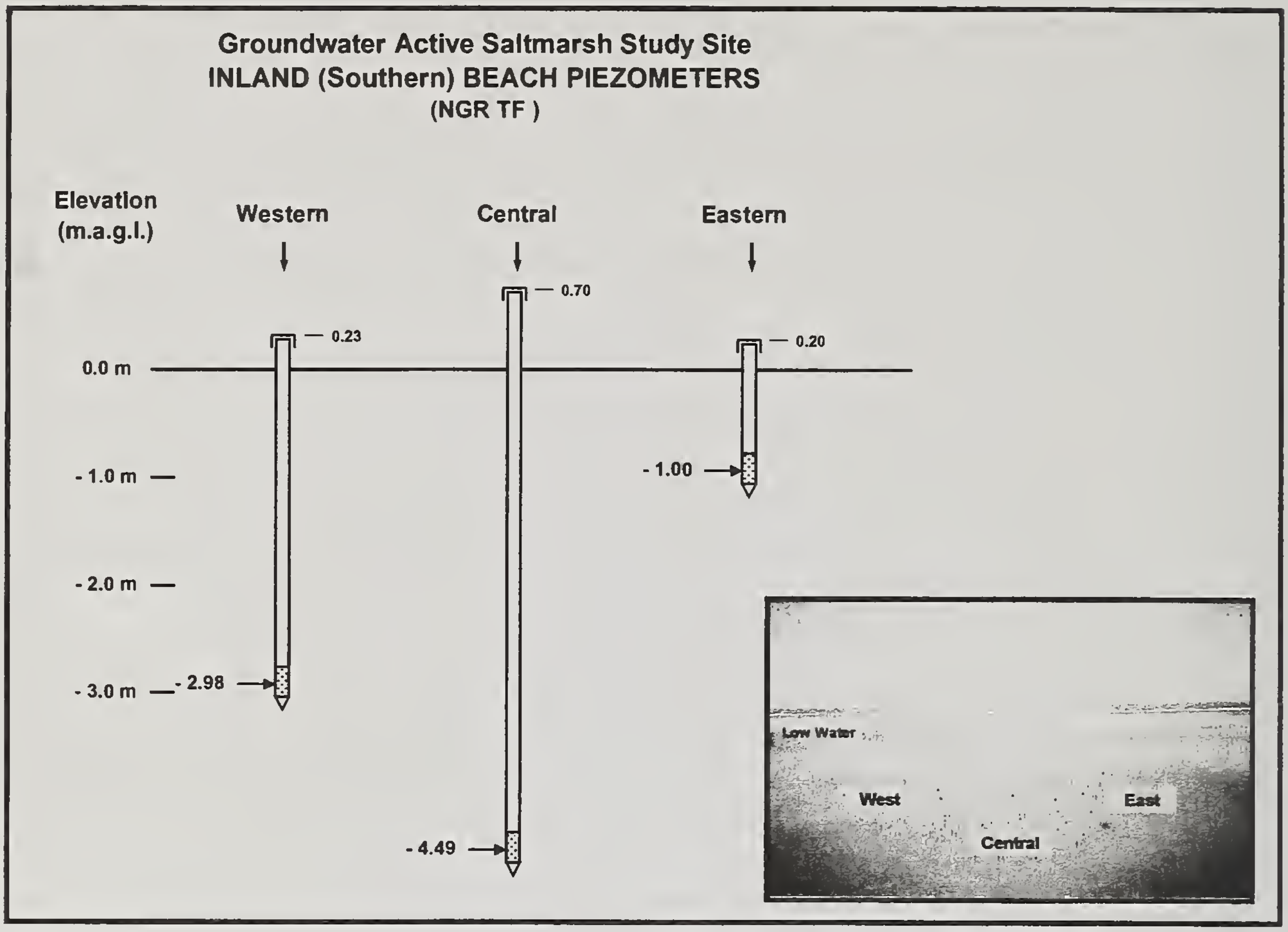
Groundwater-active Saltmarsh Study Site – Marsh Piezometers (see Fig. A1.1b)

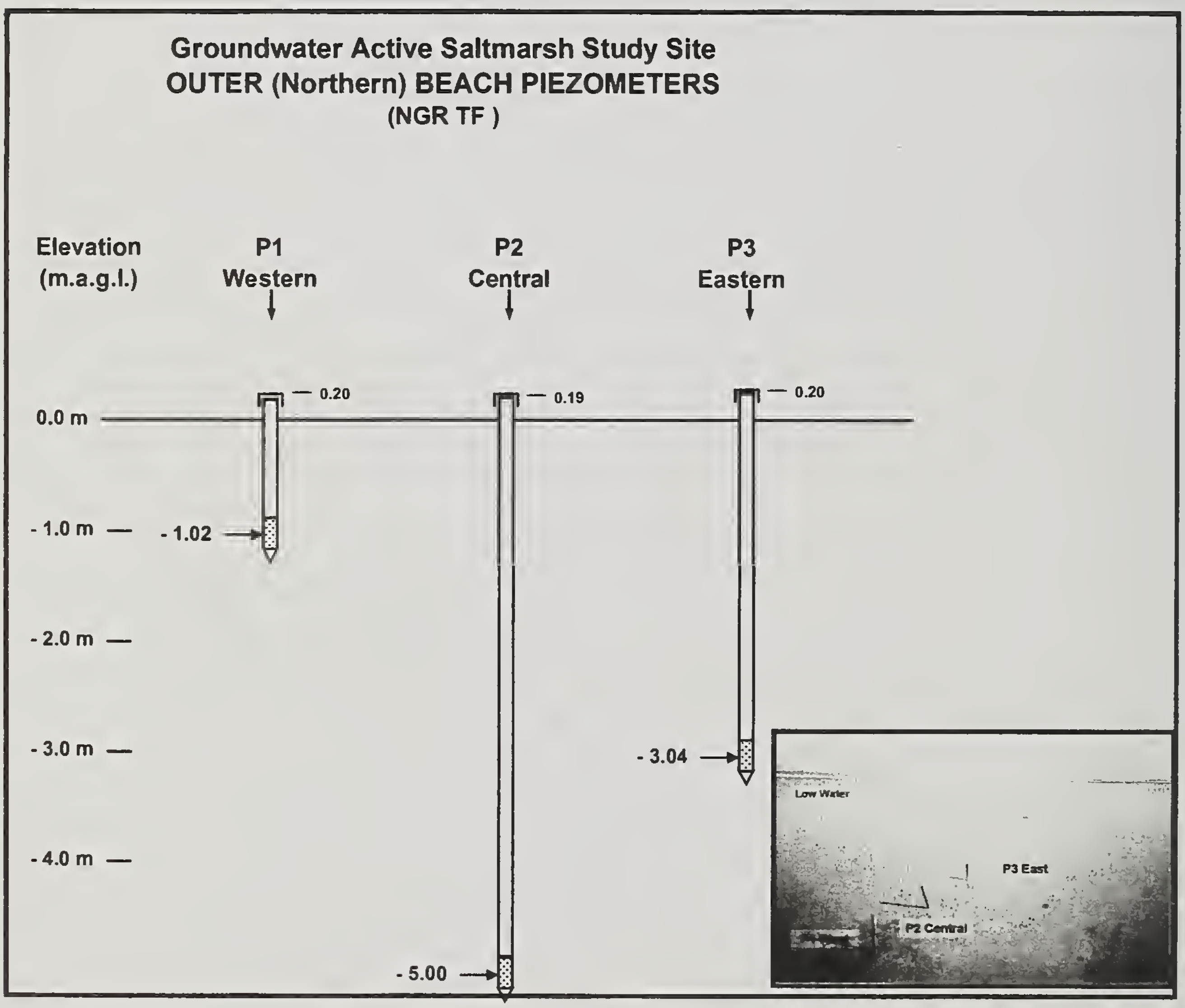




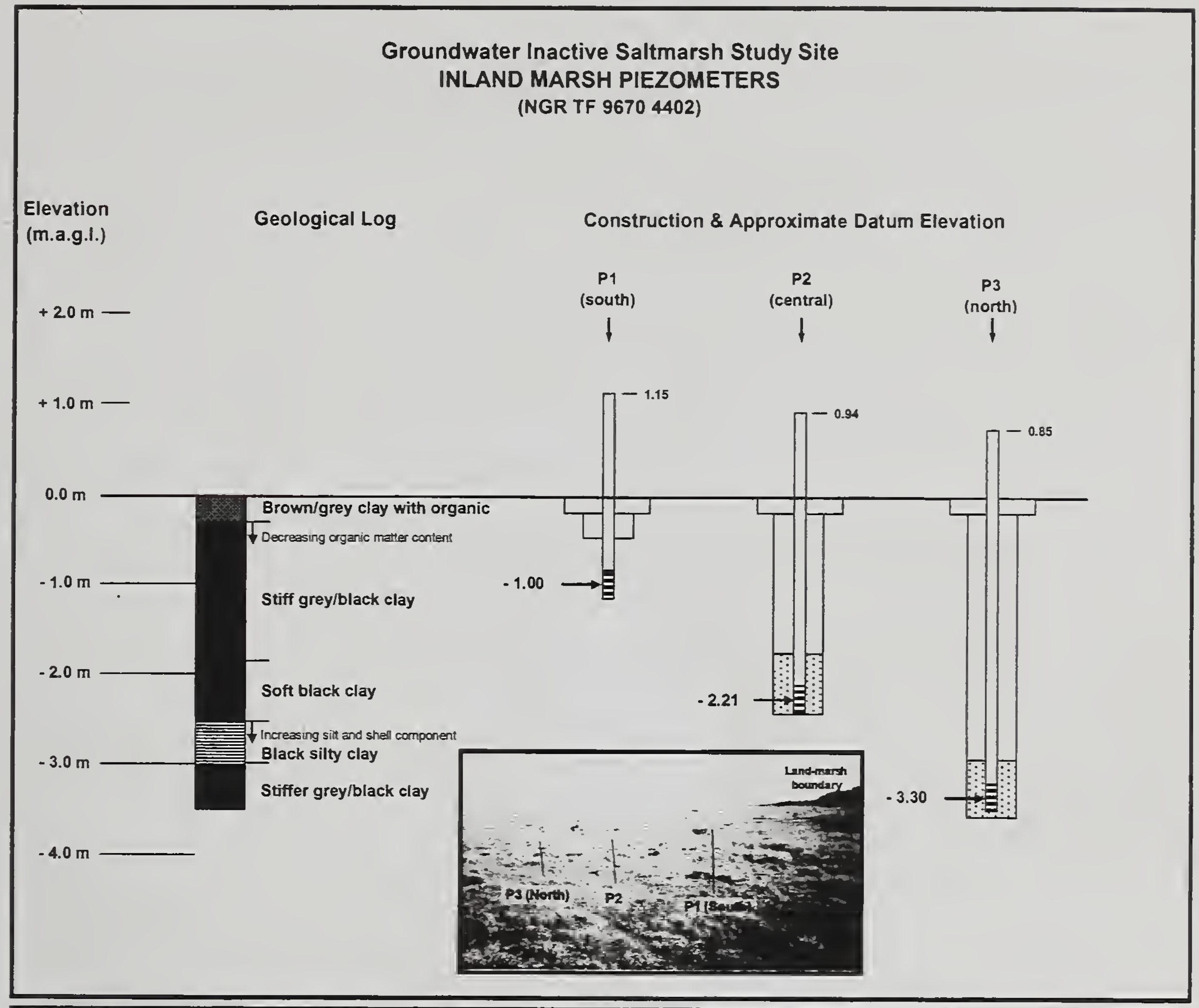

Groundwater Active Saltmarsh Study Site
OUTER MARSH PIEZOMETERS
(NGR TF 74379 44260)
Elevation (m.a.g.l.)
Geological Log
Construction & Approximate Datum Elevation
P1 (west)
P2
P3
P4 (East)
+ 1.0 m
0.0 m
- 1.0 m
- 2.0 m
- 3.0 m
- 4.0 m
Wet grey clay/mud
Peat
Grey clay/mud
1.35
0.55
1.14
0.95
- 2.80
- 1.60
- 0.88
- 2.15

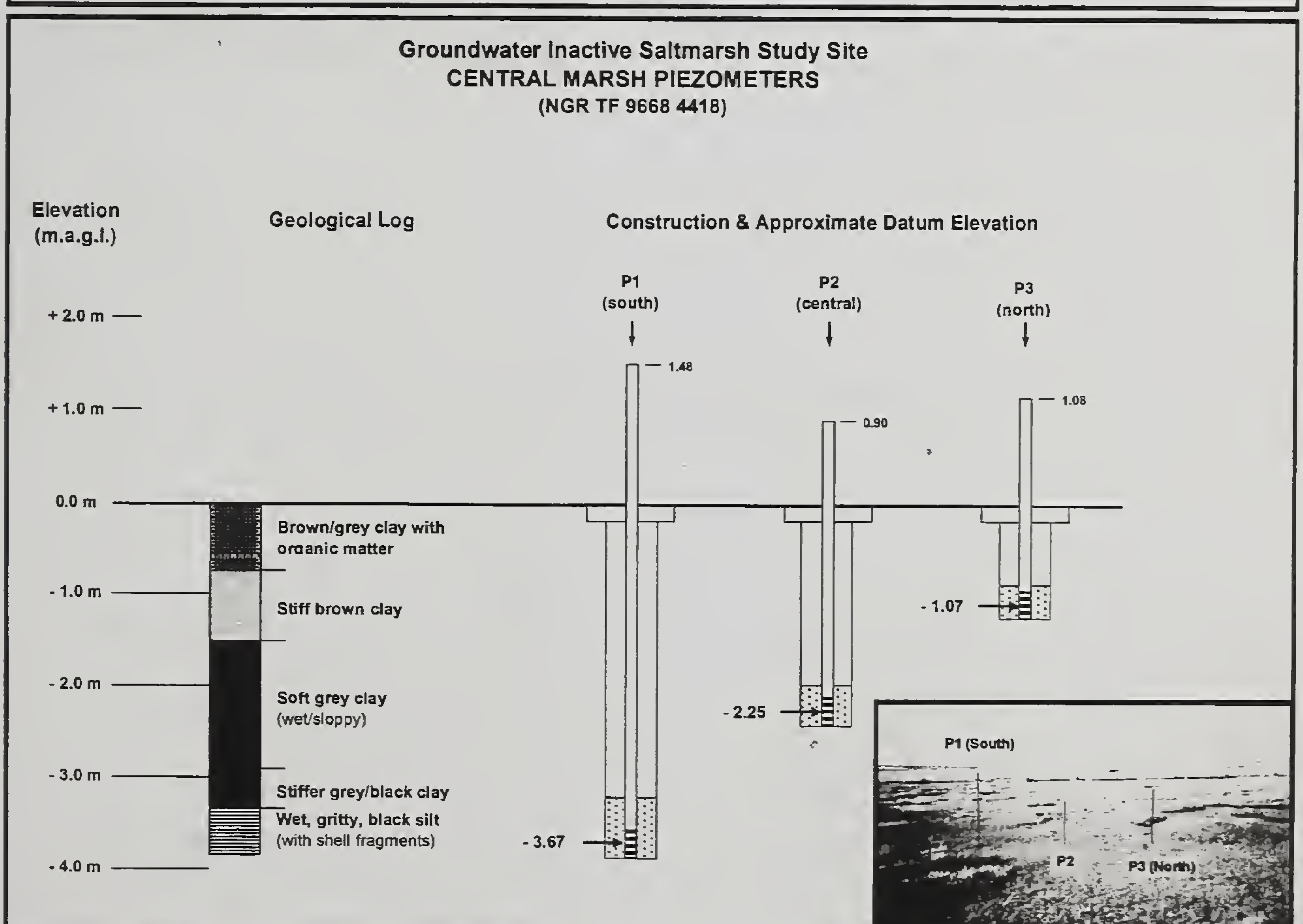
Groundwater-active Saltmarsh Study Site – Beach Piezometers (see Fig. A1.1b)

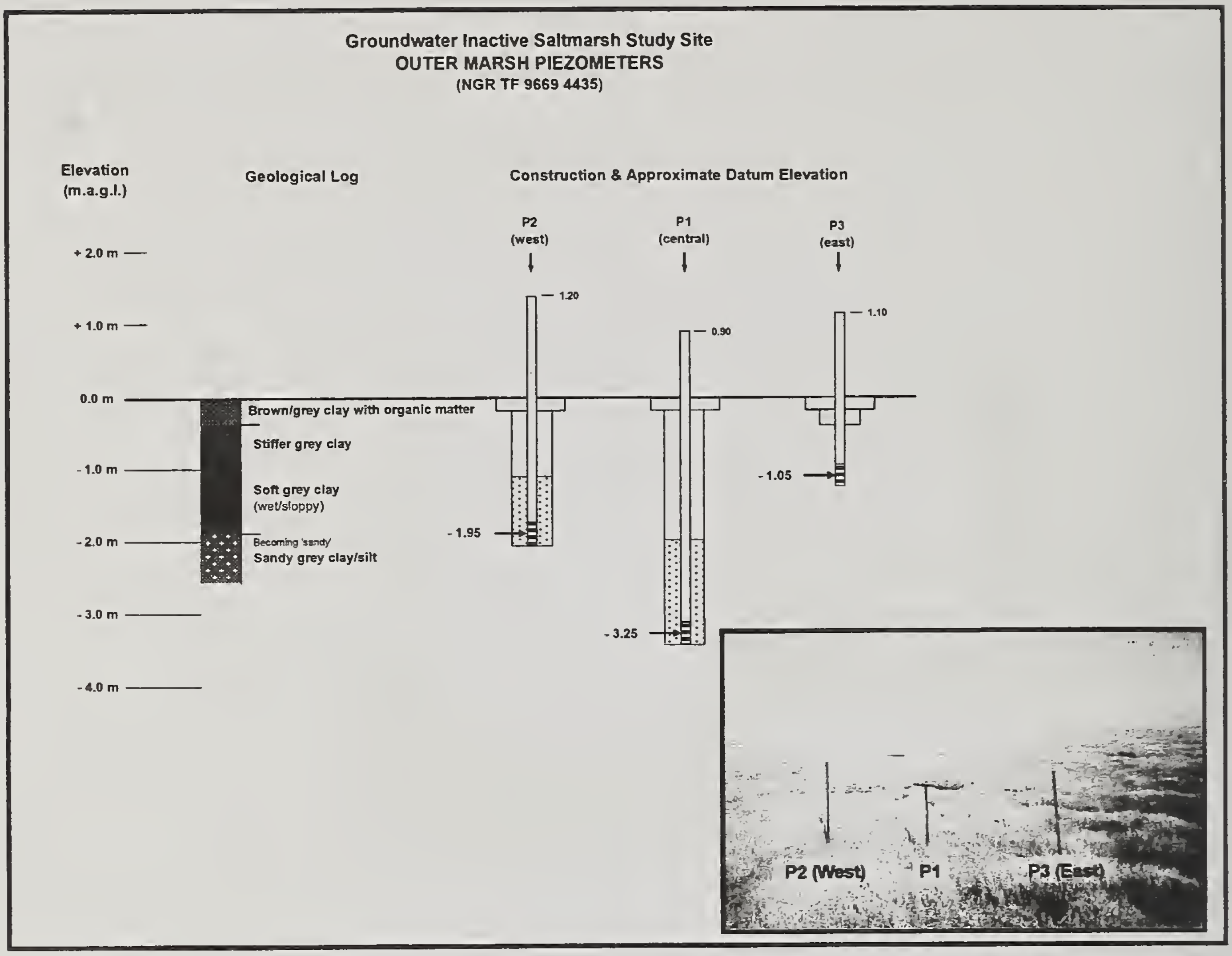




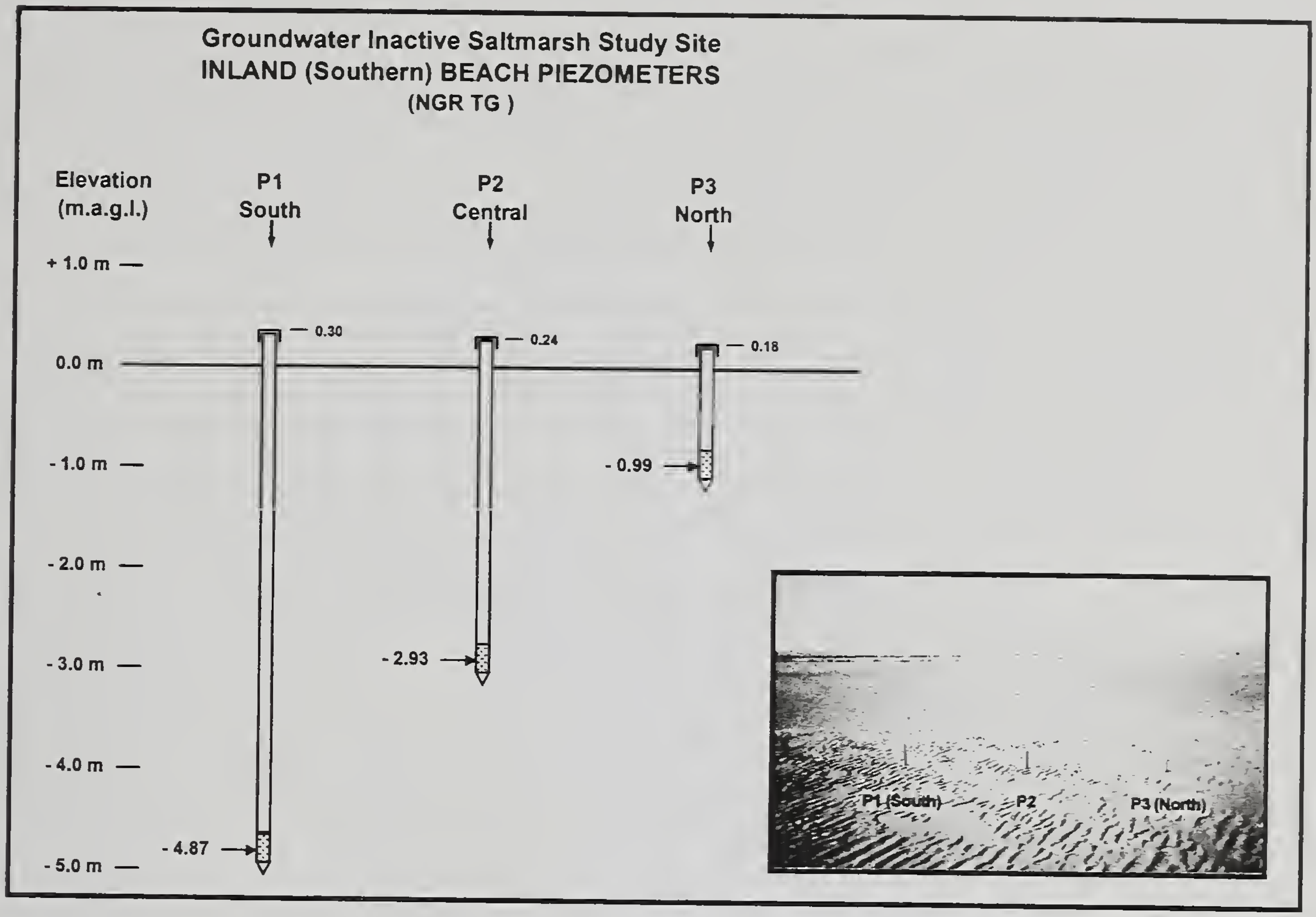
Groundwater-inactive Saltmarsh Study Site – Marsh Piezometers (see Fig. A1.2b)

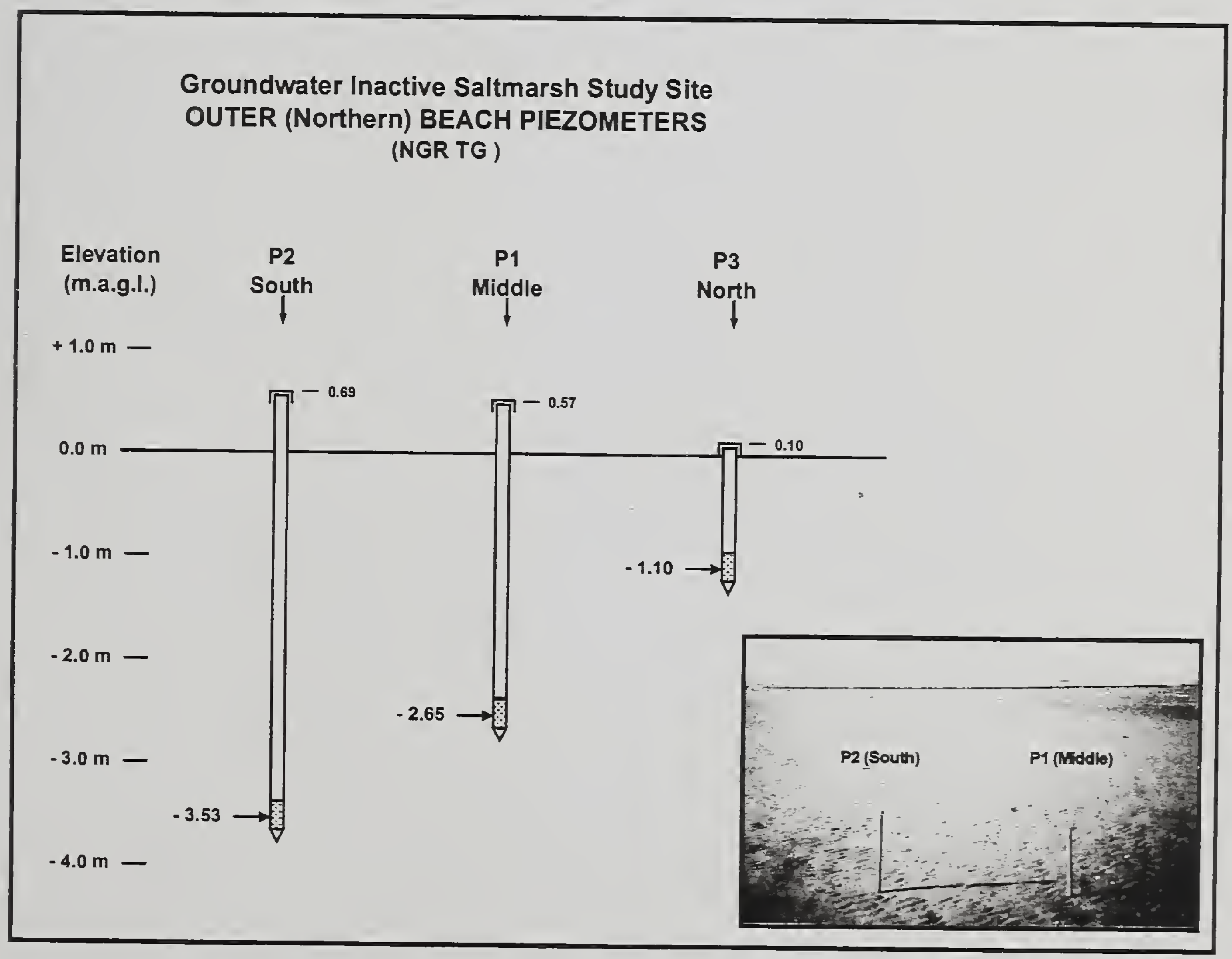





Groundwater Inactive Saltmarsh Study Site
OUTER MARSH PIEZOMETERS
(NGR TF 9669 4435)
Elevation (m.a.g.l.)
Geological Log
Construction & Approximate Datum Elevation
P2 (west)
P1 (central)
P3 (east)
+ 2.0 m
+ 1.0 m
0.0 m
- 1.0 m
- 2.0 m
- 3.0 m
- 4.0 m
1.20
0.90
1.10
Brown/grey clay with organic matter
Stiffer grey clay
Soft grey clay
(wet/sloppy)
Becoming 'sandy'
Sandy grey clay/silt
- 1.95
- 3.25
- 1.05
P2 (West)
P1
P3 (East)

Groundwater-inactive Saltmarsh Study Site – Beach Piezometers (see Fig. A1.2b)





CONTENTS

The Geological Society of Norfolk exists to promote the study and understanding of geology in East Anglia, and holds meetings throughout the year. For further details consult our Web Site (http://www.norfolkgeology.co.uk) or write to The Secretary, Geological Society of Norfolk, 32, Lenthall Close, Norwich, NR7 0UU.

Copies of the Bulletin (including older back copies) can be obtained from the editor at the address on p.1; it is issued free to members.

The figure on the front cover is Figure 1 from the paper by Donovan and Lewis in this issue of the Bulletin, showing two surfaces of a bored chalk pebble from the beach at Overstrand, north Norfolk.

ISSN0143-9286